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HYDRAULIC SYSTEM ACOUSTICAL DIAGNOSTICS.(U)
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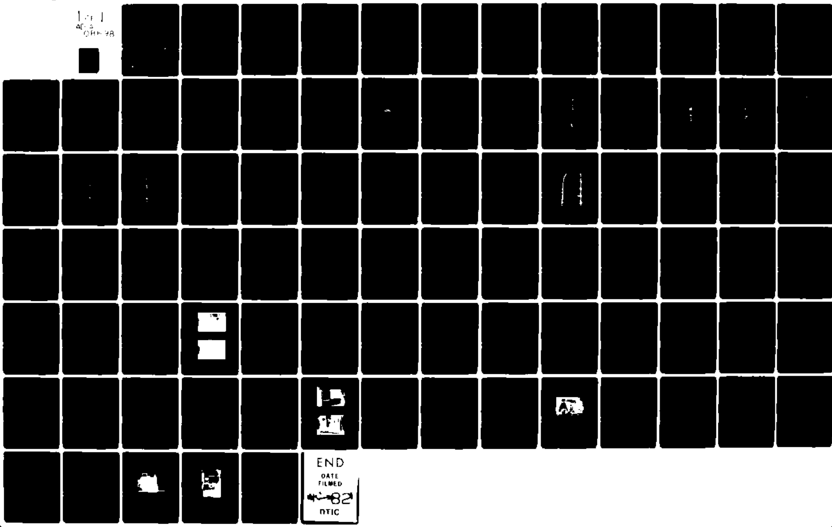

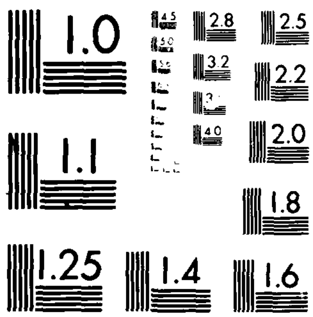

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Report No. FPRC 80-A-F1

HYDRAULIC SYSTEM ACOUSTICAL DIAGNOSTICS

FINAL REPORT

DECEMBER, 1980

PREPARED FOR

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA 22060

PREPARED BY

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CONTRACT NUMBER

DAAK70-79-C-0139

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER FPRC 80-A-F1	2. GOVT ACCESSION NO	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Hydraulic System Acoustical Diagnostics		5. TYPE OF REPORT & PERIOD COVERED Final Technical Paper September, 1979, Aug. 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Staff of the Fluid Power Research Center		8. CONTRACT OR GRANT NUMBER(s) DAAK70-79-C-0139
9. PERFORMING ORGANIZATION NAME AND ADDRESS Fluid Power Research Center Oklahoma State University Stillwater, OK 74078		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Mobility Equipment Research and Development Command, Procurement and Production Office, Fort Belvoir, VA 22060		12. REPORT DATE December 1980
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) ONRRP, Room 582 Federal Bldg. 300 East 8th Street Austin, TX 78701		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustical Diagnostics
Cavitation
Wear
Bearing Damage
Non-Intrusive Diagnostics
Fluid Power Diagnostics
Hydraulic Vane Pump

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(Over)

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ABSTRACT

This project is a continuation of previous acoustics studies conducted ~~at the Fluid Power Research Center~~ to determine if the vibration signature of hydraulic components could provide information concerning the operational health of the system. The concept of using internally produced noise to detect incipient failure is not new (the screwdriver-to-the-block trick used by automobile mechanics is a good example); however, the technique has been more of an art than a science, especially where hydraulic systems are concerned.

This study advances the previous work by applying the concept to vane pumps into which specific known degradation has been introduced. The study showed that, by using case-mounted accelerometers, significant vibratory differences can be detected and associated with given conditions.

SUMMARY

The application of non-intrusive diagnostic techniques to determine the internal health of hydraulic systems would provide hydraulic equipment users with an important maintenance tool.

Two diagnostic methods, one using microphones to detect airborne noise and the other using accelerometers to detect structureborne noise, were considered. The structureborne noise was found to be a more feasible field diagnostic method to detect failures on hydraulic components than the microphone.

By using an accelerometer mounted on the test vane pumps, detection of such malfunctions as cavitation, severe internal wear, and bearing damage was demonstrated.

A

PREFACE

This report is the Final Technical Report for the Hydraulic System Acoustical Diagnostics project, Contract DAAK70-79-C-0139. This report documents both the theoretical and experimental aspects of diagnosing hydraulic vane pump degradation acoustically.

This study was conducted by the staff of the Fluid Power Research Center, Oklahoma State University, directed by Dr. E. C. Fitch, Jr. Mr. Riichi Inoue, and Mr. R. K. King were the Principal Investigators and Mr. Don Stremme was Project Engineer. Dr. Richard Lowery of the School of Mechanical and Aerospace Engineering of Oklahoma State University provided invaluable technical assistance as a Faculty Associate.

Project personnel contributing major efforts to the project were:

A. Nipper

K. Stokes

J. Bruce

C. Totty

In addition, various members of the Fluid Power Research Center staff contributed to this study.

The Contract Officer Technical Representatives for this contract were Mr. James Dillon and Mr. Delmar Craft.

The contract was monitored by the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.

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CHAPTER I
INTRODUCTION

Most of the current diagnostic techniques to detect or predict failures of the fluid power system require shut-down of the system operation. A non-intrusive technique is desirable which would allow component performance analysis to be performed with no down time.

In the process of transmitting energy by means of fluid, some energy is dissipated as vibration and acoustical noise. As the performance of a component degrades, more energy is emitted as a result of the component's decreased efficiency. Hence, machine performance degradation can possibly be monitored by measuring vibration and noise.

This document is the final report of the first phase of a project to determine if distinctive, repeatable signals can be obtained to show that such a monitoring technique is feasible. To investigate this feasibility, two diagnostic methods were evaluated in conjunction with the signals generated by vane pumps: one using a microphone to measure airborne noise and the other using an accelerometer to monitor vibration. Experimental test data obtained by the two methods are presented, and the comparative diagnostic capabilities of the methods are discussed.

CHAPTER II

TECHNICAL BACKGROUND

The goal of the project was to develop a potential non-intrusive diagnostic technique which could be packaged into a dedicated field system. The concept of a non-intrusive diagnostics system can be simplified into three phases as illustrated in Fig. 2-1.

Transduction is associated with the conversion of a desired measurand into an equivalent electrical waveform. In this study, the measurand is airborne and structureborne noise emission, the corresponding transducers being microphones and accelerometers, respectively.

Data processing consists of digitizing the electrical waveform and processing the data in the desired format. Through this process, the incoming signature from the transducer would be averaged and reduced to the desired format by a Fourier analysis or other analytical procedures. The data are then presented in the desired format for analysis. Once the data have been analyzed, an evaluation of machine condition can be achieved by a preprogrammed microcomputer.

The hardware of diagnostic systems consists of transducers and a microprocessor to transform the data into the desired format and to proceed through the necessary data reduction. Fig. 2-2 illustrates the possible extent of a diagnostic system and was used as a guide throughout the project. The figure proposed three different systems that

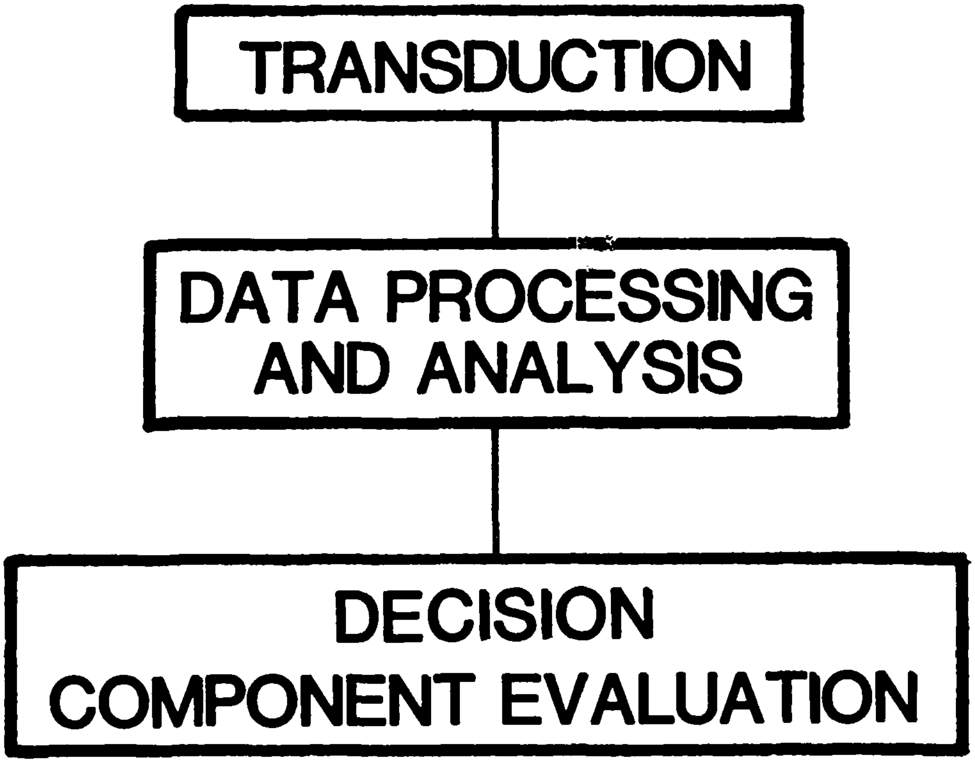

FIG. 2-1. Non-Intrusive Diagnostic System

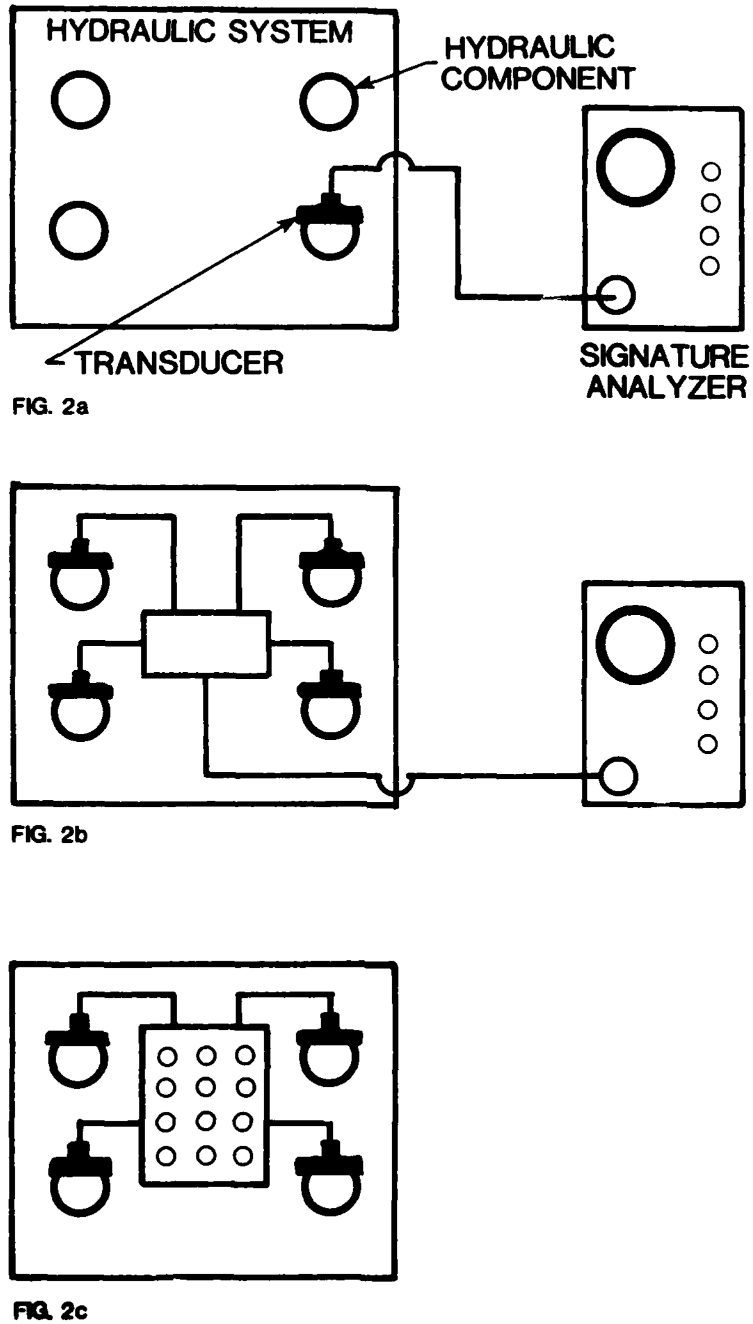

FIG. 2-2. Diagnostic System for Field Application

could be utilized. Fig. 2-2a illustrates a complete portable field unit, in which the transducer is temporarily placed on the component under test and analyzed by a portable noise signature analyzer. Fig. 2-2b illustrates the concept of having the transducers as a permanent installation of the hydraulic system. The portable analyzer is connected to a central unit which connects the analyzer to various components. Fig. 2-2c represents a much more elaborate system in which both the transducers and the analyzer are permanently installed on the system. Fig. 2-2c, although more expensive than others, offers the advantage of utilizing a microprocessor that can be used for other control systems on the hydraulic machine. Another distinction in the method illustrated in Fig. 2-2c is it proposes that the analysis of the component be exclusive of human interface. This eliminates the chance of misinterpretation. Two types of transducers are available for the diagnostic system; a piezoelectric accelerometer and a microphone. The piezoelectric accelerometer, due to its ruggedness, could be utilized in all three proposed systems, while the microphone would be applicable in Fig. 2-2a only.

CHAPTER III

EVALUATION OF TRANSDUCERS IN DIAGNOSTIC METHOD

The initial phase of the project began by choosing the method of transduction to be utilized for the development of a non-intrusive diagnostic technique. Microphones and accelerometers were evaluated. Both methods are currently being utilized in the area of machinery diagnostics. The transducer methods were compared on the basis of experimental performance and compatibility with field environments.

The energy dissipated by a component in the form of vibration provides information relating to its operating condition. The vibration of a hydraulic pump is the result of the energy conversion process (mechanical and hydraulic) in addition to the mechanical impact that takes place during the pump's operation. Flow production and mechanical interactions transmit energy in the form of vibration throughout the pump's housing. The vibratory action of the pump housing produces air pulsations or soundwaves which constitute the airborne emissions of the pump. It has been experimentally verified that the vibration characteristics of an operating pump can provide information concerning the operating integrity of the component. The transducers were chosen to measure the vibration characteristics of the pump in its two forms--airborne noise (microphone) and structureborne noise (accelerometer).

MICROPHONE METHOD

Any object that vibrates will generate sound due to the movement

of air in the vicinity of the object. The simplest form of noise source is a sphere that vibrates uniformly over its entire surface. This source radiates sound in all directions from its geometric center. It then may be considered as a "point" source insofar as radiated sound is concerned.

If this source is far from any other source, then the sound field produced is called the free field. As a rule of thumb, a microphone is said to be in the free field when its distance from the source is greater than one wavelength of the lowest frequency to be measured.

The free field condition does not occur in practice because sound is reflected from nearby objects such as floors, walls, and ceilings. This phenomenon can be controlled in the laboratory environment, but controlling the field environment is virtually impossible; however, if one is concerned only with changes in a signature rather than an absolute noise signature, the free sound field is not necessary. Such is the case when diagnosing changes in the performance of fluid power components. Therefore, the microphone data are obtained with the transducer positioned in the near sound field or "near field." A microphone is said to be in the near field when the distance from the transducer to the noise source is no greater than one wavelength of the lowest frequency to be measured, and preferably much less.

The purpose of near field noise measurements is to isolate the microphone from any background noise. When testing a fluid power pump,

the microphone should "see" only the pump noise, and it should be blind to noise from piping, valves, drive shafts, and so forth. Thereforth, the microphone should be placed very close to the pump's surface. The microphone position for the purposes of this project was 4 mm from the pump's surface, centered on the vane rotor housing.

ACCELEROMETER METHOD

The use of vibration signature analysis is a logical choice, since it involves mechanical events such as impact, rolling, and sliding actions inherent in rotating machinery. The waveform of the vibration of a component contains a great deal of diagnostic information. For example, the timing of events with respect to each other may be of importance. In addition, the presence or absence of particular noises indicative of mechanical events is important when evaluating component performance.

Vibration levels are usually monitored with transducers called accelerometers. These are mounted rigidly to the test component and produce a voltage proportional to the acceleration of the component structure. There are several types of accelerometers available, but the piezoelectric is the most common. These transducers have large output-voltage signals and are available with very high natural frequencies. Typical construction of piezoelectric accelerometer is shown in Fig. 3-1.

In most measurement systems, the accelerometer is used in conjunction with a high-impendance charge amplifier to obtain accurate low-frequency

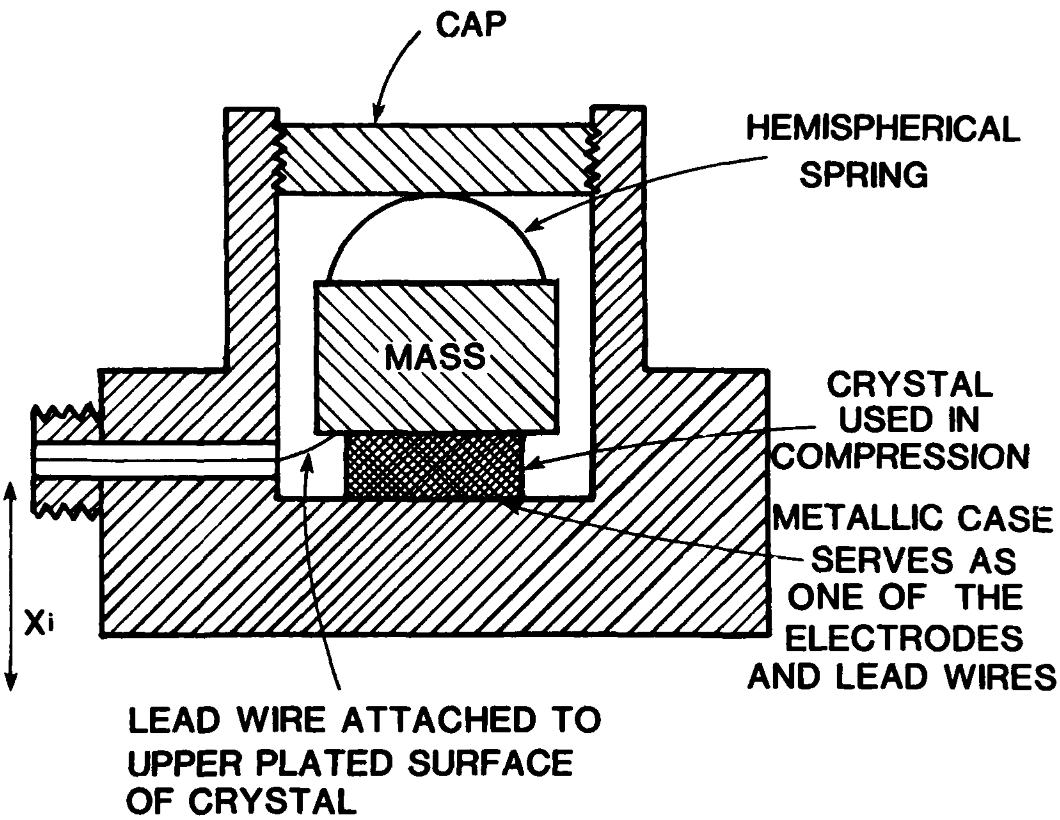

FIG. 3-1. Piezoelectric Accelerometer Construction

response. Furthermore, charge amplifiers are relatively insensitive to cable capacitance which is essential when long transmission cables are used. A typical vibration measurement system is shown in Fig. 3-2.

Size selection of an accelerometer is important since a large accelerometer mounted on a small component will alter the component's dynamic characteristics. These transducers are available in a wide variety of sizes; however, there are trade-offs to be considered. As a rule, small accelerometers are less sensitive than larger ones but have higher resonant frequencies, which is often desirable.

EXPERIMENTAL COMPARISON TEST

Two fluid power vane pumps were tested which were of the same manufacturer's series with the same displacement. Each pump has 12 vanes that divide the flow into discrete volumes. The pumps were driven at 1200 rpm. A peak is expected when each vane passes by the transducer. Since there are 12 vanes, the fundamental vane passage frequency is 240 Hz.

The first few harmonics of the fundamental frequency spectrum can be observed on the frequency spectrum graph. If the fundamental frequency is given by f(o), then the first harmonic is 2f(o), the second is 3f(o), and so on. This gives us the first harmonic at 480 Hz, the second at 720 Hz, and third at 960 Hz. Higher order harmonics can also be seen, Fig. 3-3. Note that the harmonics shift around somewhat. This can be attributed to the fluctuations in the V-belt drive. The data in Fig. 3-3

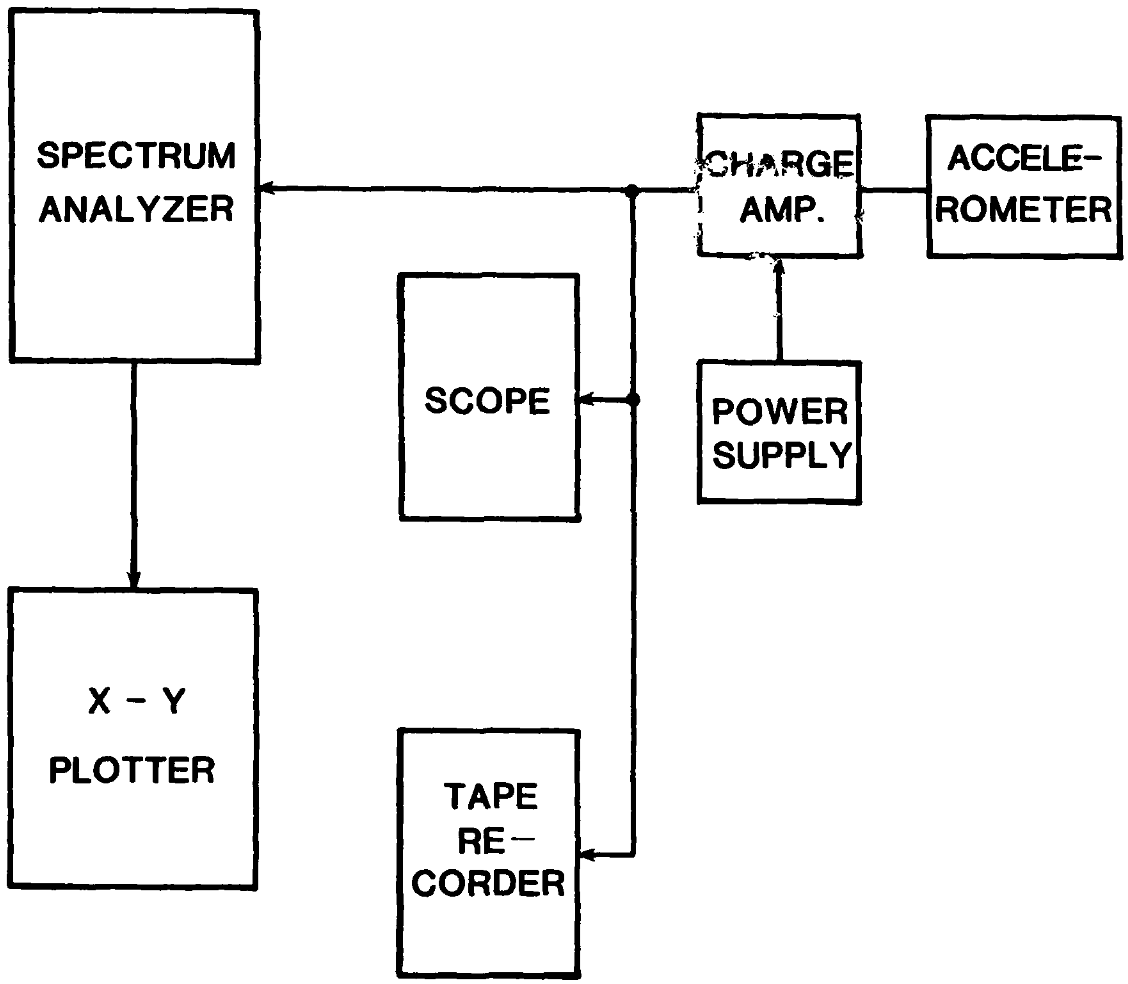

FIG. 3-2. A Typical Vibration Measurement System

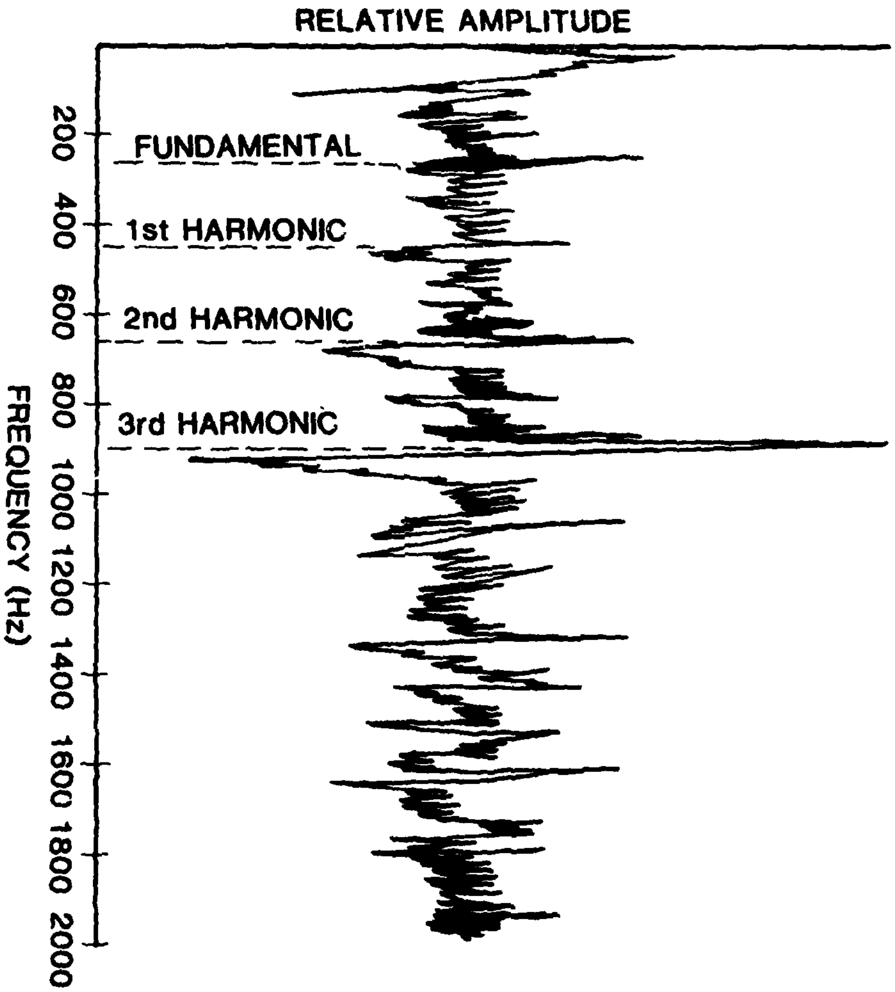

FIG. 3-3. Vane Pump Frequency Spectrum by Accelerometer in Normal Operation

were obtained with a BBN 507 accelerometer mounted on vane rotor housing. A charge pump was installed in the inlet line to keep the pump inlet pressure positive, thereby eliminating cavitation. Microphone data are presented in Fig. 3-4 with no change in pump operation. It is obvious that the vane passage harmonics are not nearly as clear in Fig. 3-3, but they do appear. Tests corresponding with Figs. 3-3 and 3-4 were conducted with the pump operation conditions in Appendix B.

Cavitation data recorded with the accelerometer and microphone are shown in Figs. 3-5 and 3-6, respectively. To obtain cavitation, the charge pump was removed from the inlet side of the pump, and inlet pressure was lowered by throttling the line. Otherwise, the operating parameters are identical to those in the previous tests. The vane passage fundamental frequency with its first few harmonics can again be seen. The accelerometer data in Fig. 3-5 contain hamonics up to the sixth. While the higher order harmonics do not coincide exactly with the appropriate multiple of the fundamental frequency, this is to be expected in a V-belt drive system. The important point is that the microphone data in Fig. 3-6 also contain the higher order harmonics but they are covered up by "noise".

The final test involved vane damage similar to that which could occur in the field. The pump was disassembled and a small groove was made with a file on the wiping edge of a single vane. The pump was then installed in the system with other operating parameters remaining unchanged. In order to simulate vane damage only, the charge pump was

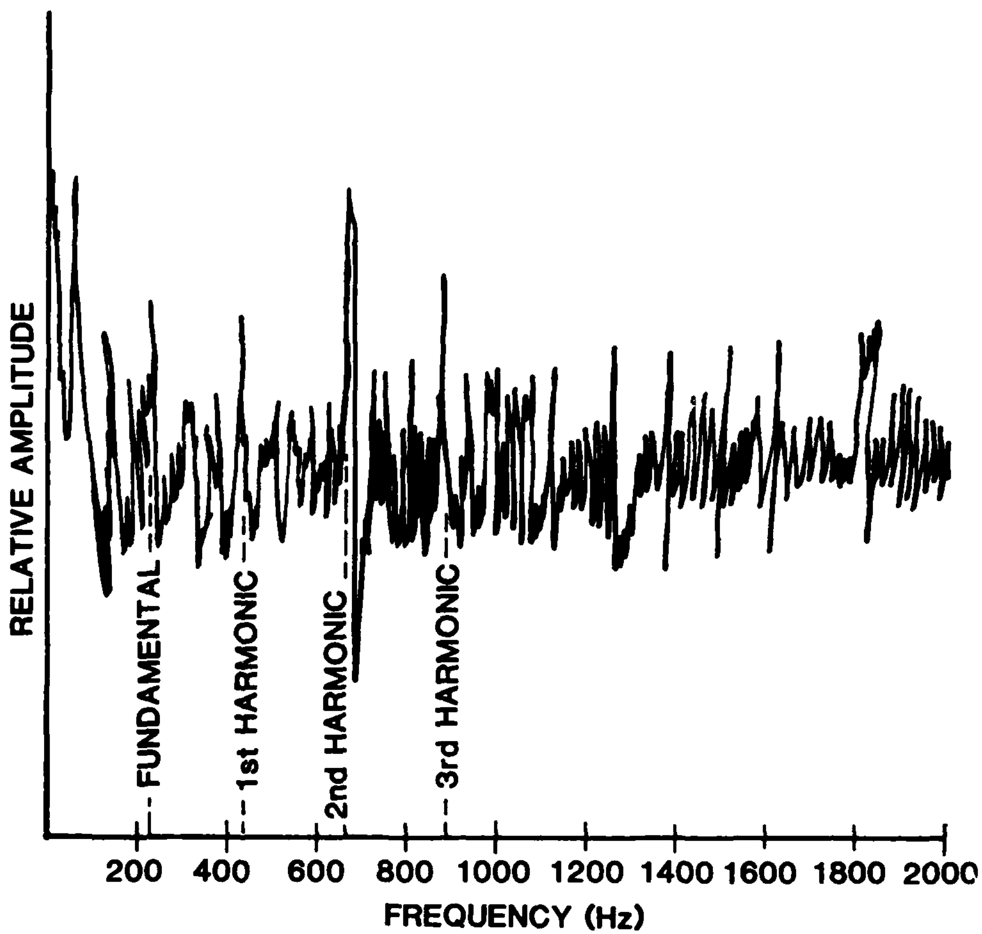

FIG. 3-4. Vane Pump Frequency Spectrum by Microphone in Normal Operation

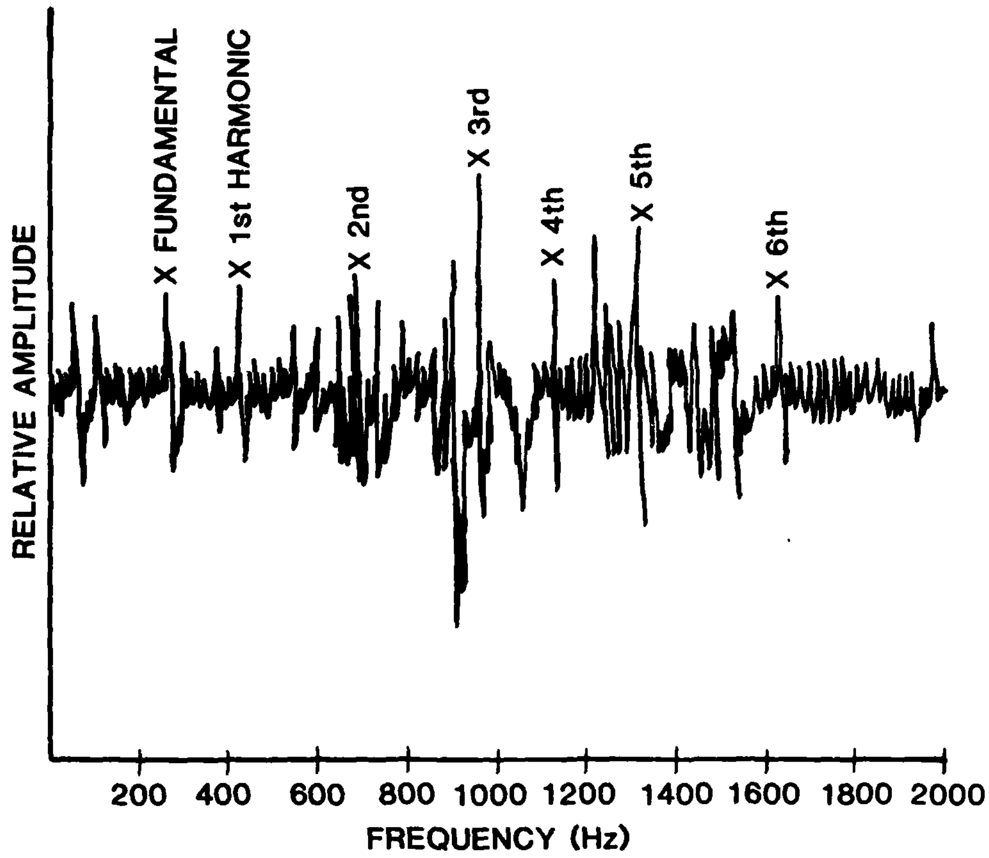

FIG. 3-5. Vane Pump Frequency Spectrum by Accelerometer in Cavitation

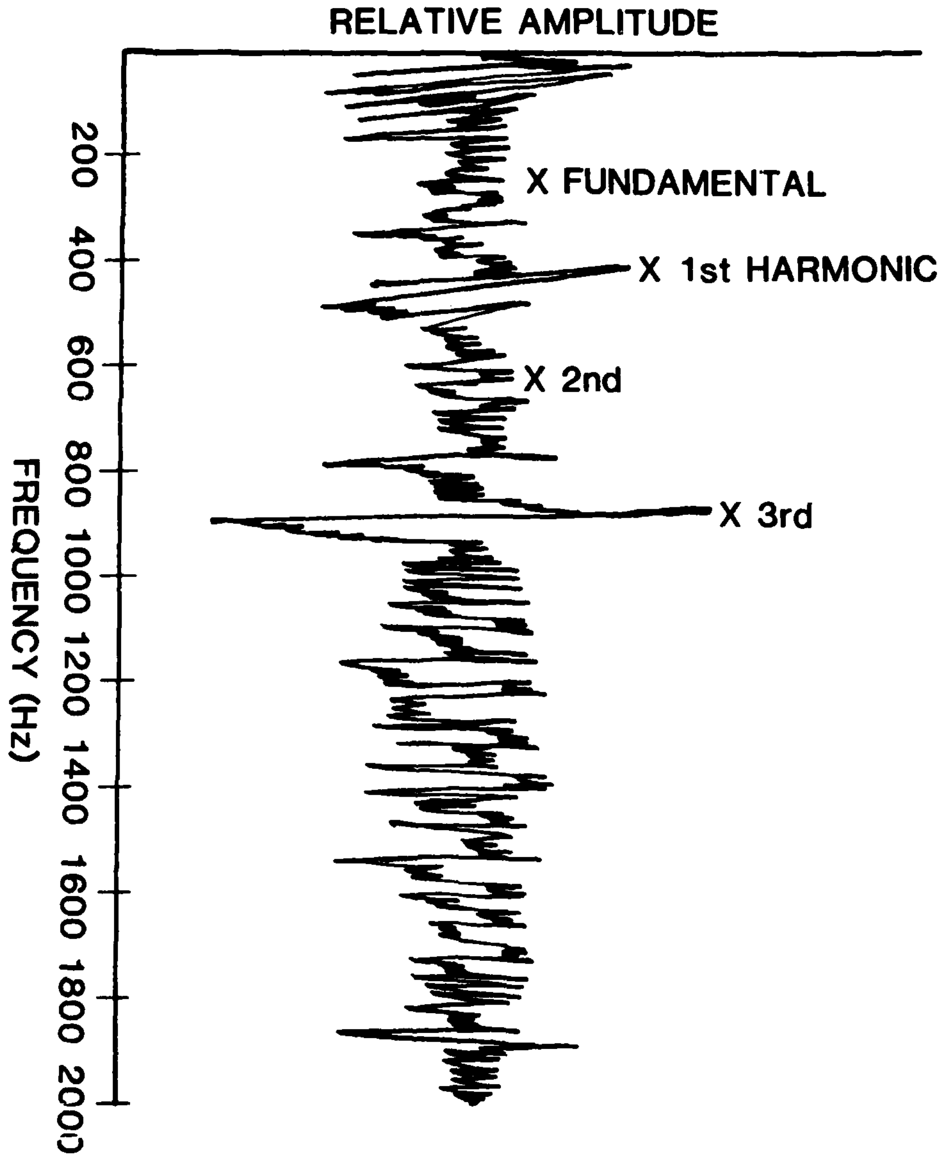

FIG. 3-6. Vane Pump Frequency Spectrum by Microphone in Cavitation

reinstalled in the pump inlet line. Figs. 3-7 and 3-8 represent accelerometer and microphone data, respectively, for induced vane damage.

TEST DATA INTERPRETATION

From the test data shown in Figs. 3-3 to 3-8, it is obvious that the frequency spectra change when degradation occurs. The change of amplitudes at fundamental and harmonic frequencies of the frequency spectra are summarized in Figs. 3-9 and 3-10. Fig. 3-9 shows the change of amplitudes due to cavitation and vane damage as monitored by an accelerometer. Cavitation decreases only the second and the third harmonic amplitudes significantly, while vane damage decreases all fundamental, first, second, and third harmonic amplitudes down to 40 percent of the original values.

Fig. 3-10 shows the change of amplitudes as monitored by microphone. Cavitation decreases fundamental and second harmonic amplitudes significantly; whereas, vane damage decreases fundamental, first, and second harmonic amplitudes.

The above observation proves the possibility that failures can be detected and identified by monitoring the frequency spectra; however, it should be noted that the accelerometer method has failure detection criteria which are different from the microphone method. This is due to the fact that the former measures structureborne vibration while the latter measures airborne noise.

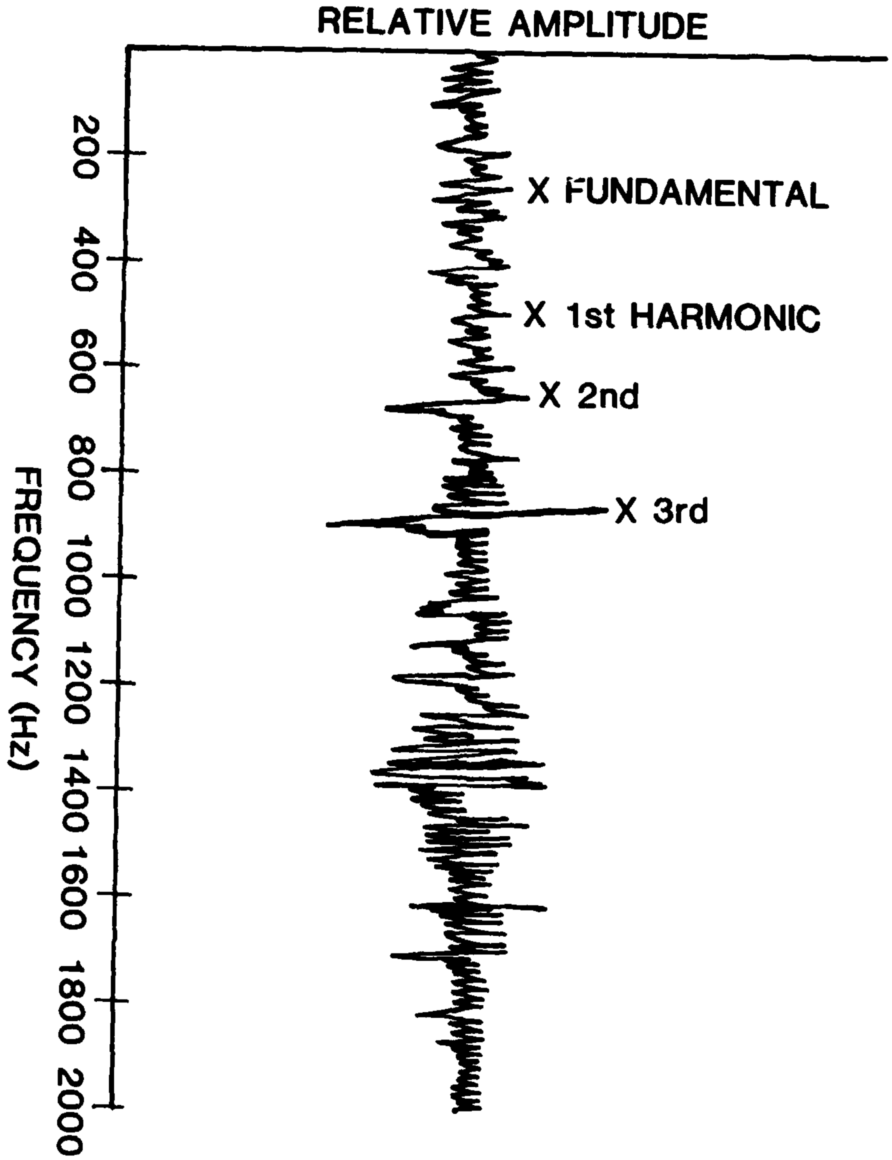

FIG. 3-7. Vane Pump Frequency Spectrum by Accelerometer with Vane Damage

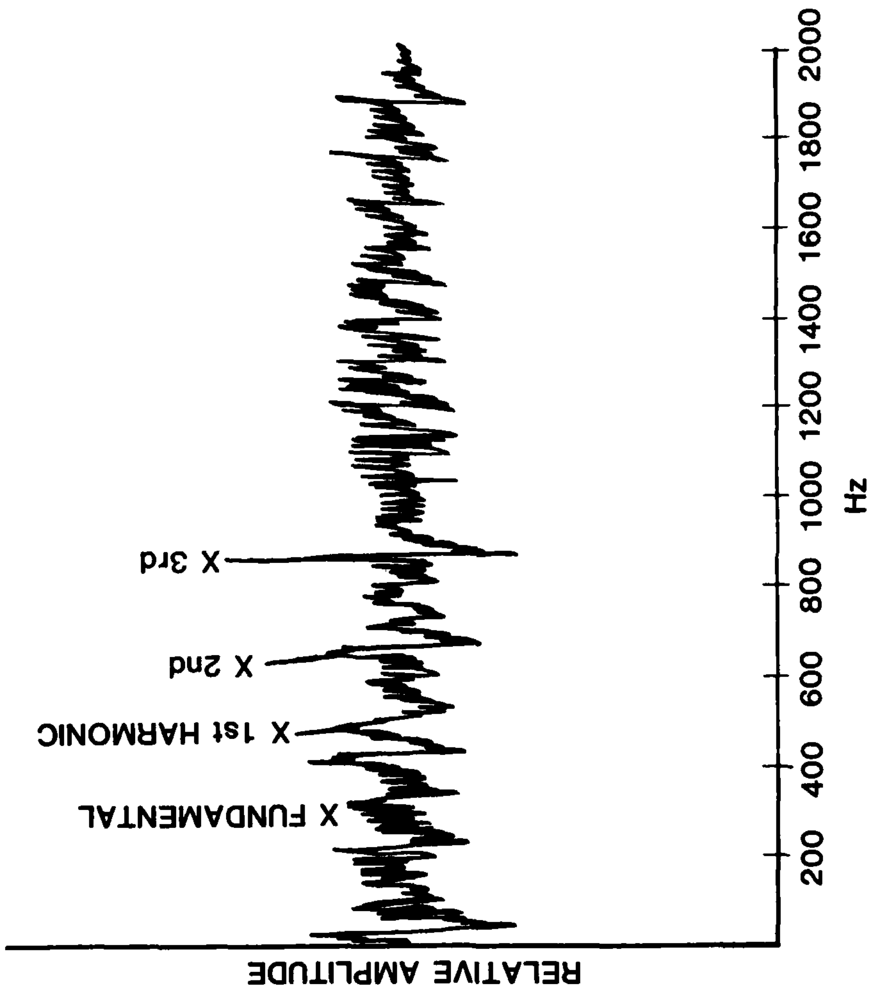

FIG. 3-8. Vane Pump Frequency Spectrum by Microphone with Vane Damage

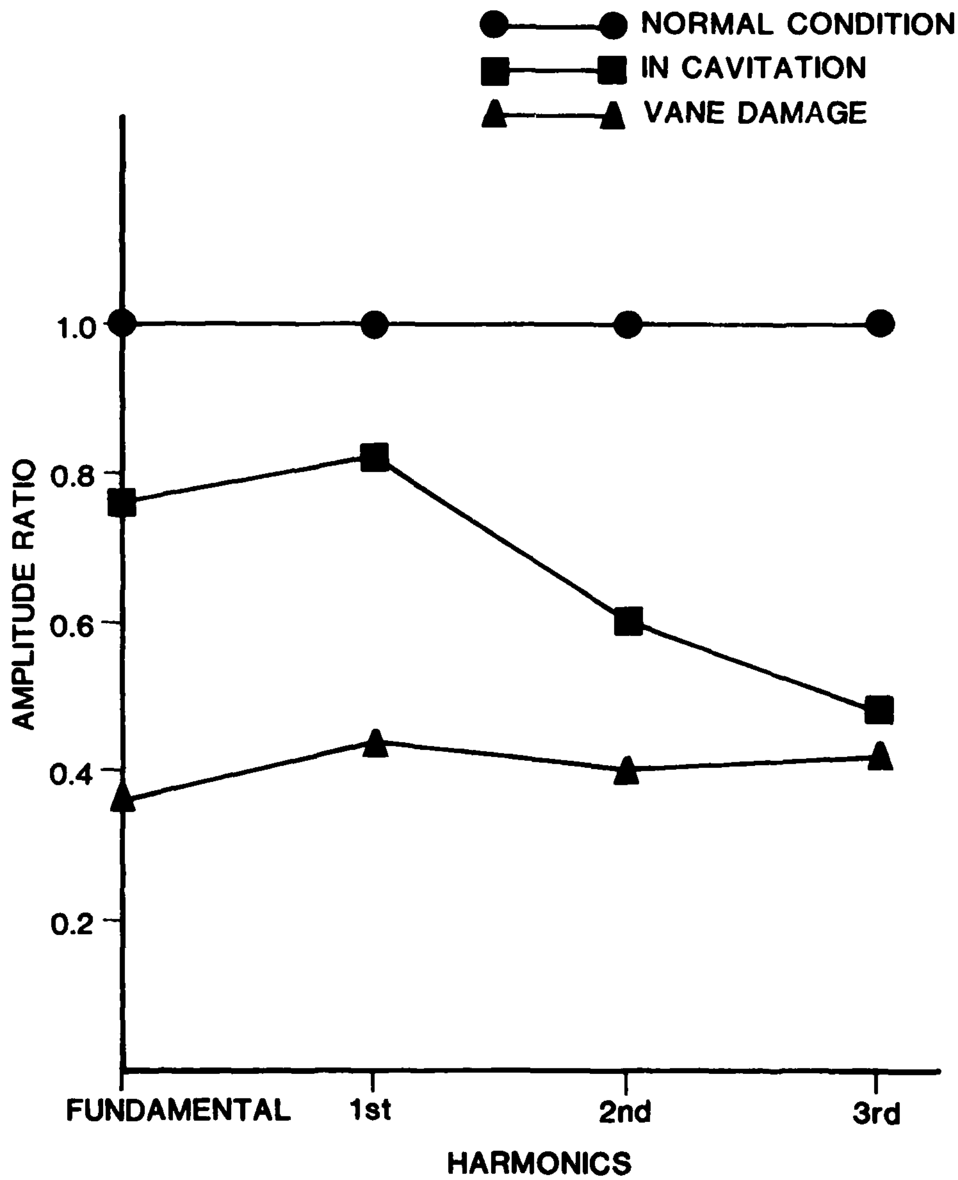

FIG. 3-9. Changes of Harmonic Frequency Amplitudes Due to Failures (Accelerometer)

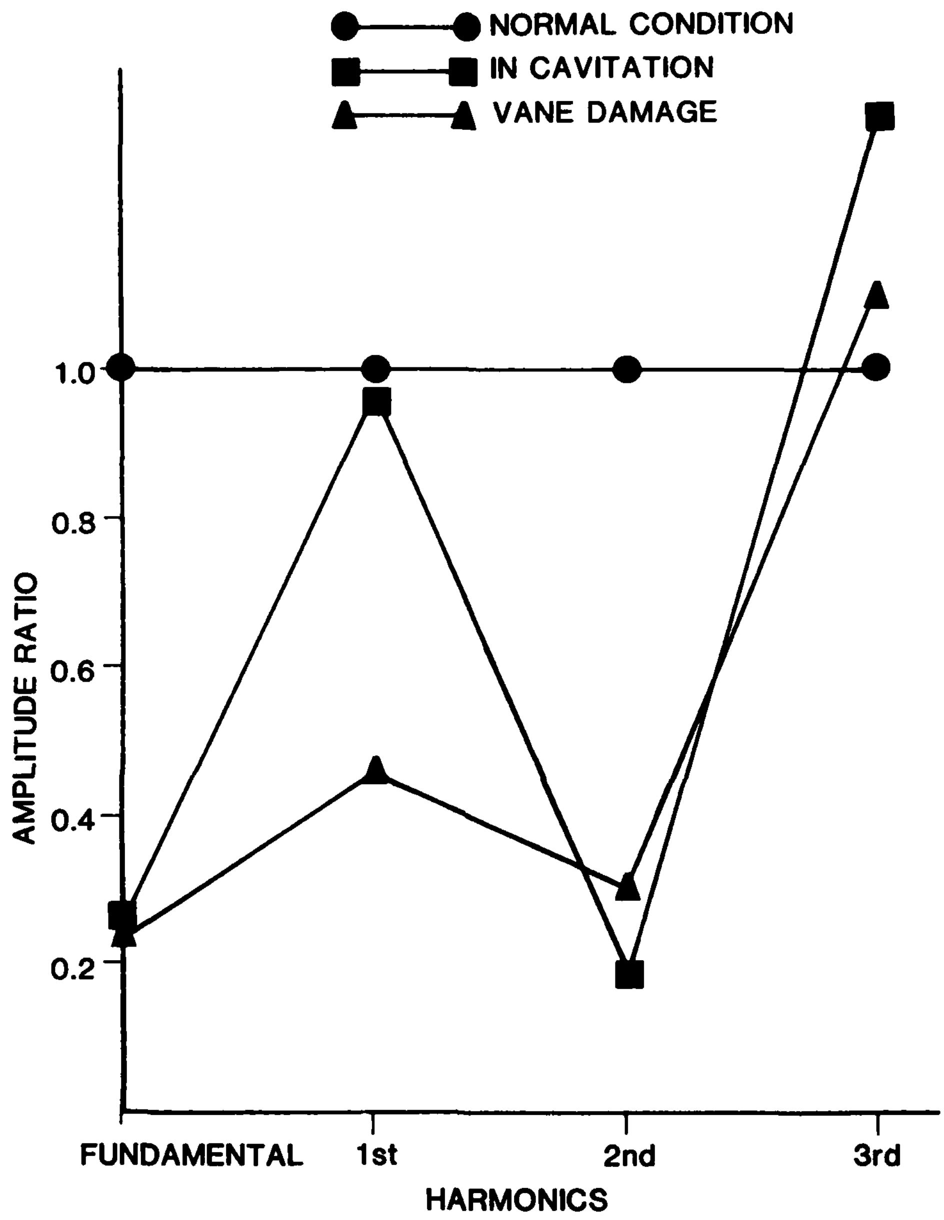

FIG. 3-10. Changes of Harmonic Frequency Amplitudes Due to Failures (Microphone)

TRANSDUCER EVALUATION

Although the two diagnostic transducers, the microphone, and the accelerometer were found to be capable of detecting failures of hydraulic components, the failure criteria when using the microphone are different from those using the accelerometer. The criteria with the accelerometer are more consistent from a decision-making standpoint because the abnormal amplitude ratios are always less than the normal ones; whereas, the abnormal amplitude ratios with the microphone are either less or more than the normal ones.

Another important aspect to be considered as a field diagnostic transducer is a degree of environmental limitations. The limitations of each transducer are presented in Table 3-1. Each transducer has a

Table 3-1. Transducer Limitations

Item of Limitation	Microphone	Accelerometer
Sensitivity	Sensitivity to source Directivity	Cross-axis sensitivity
Influence	Reflections and influence of microphones present on the measurement	Mass loading; influence of the accelerometer on the vibration of the surface which it is measuring
Environmental Sensitivity	A. Temperature B. Humidity C. Moisture Condensation D. Vibration E. Wind - "Wind Noise"	A. Temperature Gradient B. Humidity C. Sound Pressure

certain limitation corresponding to environmental effects. However, the accelerometer, because of its enclosed construction, can withstand a more extreme field environment.

The limitations expressed in Table 3-1 can be compensated in the laboratory, but the environmental sensitivity is a handicap for the microphone in the field application. The ruggedness of the accelerometer lends itself the potential to be installed as a permanent part of a hydraulic system as proposed in Figs. 2-2a and 2-2b.

From the above considerations, it was decided to use the accelerometer to demonstrate and verify the acoustical diagnostic method with experimental tests.

CHAPTER IV

ACOUSTICAL DIAGNOSTIC TESTS

TEST PROCEDURE

Before the tests pumps were subjected to the diagnostic tests, the pump break-in was achieved. The pump break-in procedure followed the manufacturer's specifications. Details of the break-in can be found in Appendix A. The pumps were operated under normal operating conditions and the corresponding baseline signature was recorded. The baseline signature corresponds to the frequency spectrum of the undamaged component under specified operating conditions of speed, pressure and temperature. The pump would be subjected to abnormal operating conditions of wear, cavitation, and damaged bearing with the corresponding frequency spectrum being analyzed.

The data processed through a spectrum analyzer and the amplitude (A_f) corresponding to the fundamental and harmonic frequencies were recorded. The diagnostic test procedures and operating conditions can be found in Appendix B. Pump-mounted accelerometers were used in all tests discussed in the remainder of this report.

The test procedure used during the project was based on a diagnostic method which could be used in a field diagnostic unit. The diagnostic method pertains to processing of the input signature from the transducer and presenting the data in the desired format for analysis.

A real time spectrum analyzer was used during the project. The analyzer received the analog signal from the accelerometer and converted the electrical waveform into a time and frequency representation. Both the time and frequency domain are illustrated in Fig. 4-1.

The figure represents the time and frequency display of the vibration signature from a hydraulic vane pump as seen on the CRT of the spectrum analyzer.

The upper graticule represents the time domain signature of the vibration which shows the vibration amplitude versus time. The lower graticule is a display of the same signal in the frequency domain; amplitude versus frequency. The time domain analysis is a very effective method for qualitative analysis of an incoming waveform. The frequency domain is a quantitative analysis of how the energy within the waveform is dispersed versus frequency.

The diagnostic method will utilize the frequency domain analysis which also is referred to as spectrum analysis.

The frequency range of investigation must be selected prior to transducer selection. The frequency range will depend on the components under investigation. The project tested hydraulic vane pumps which were of the same manufacturers' series with the same displacement. Each pump has 12 vanes which divide the flow into discrete volumes. The pumps were

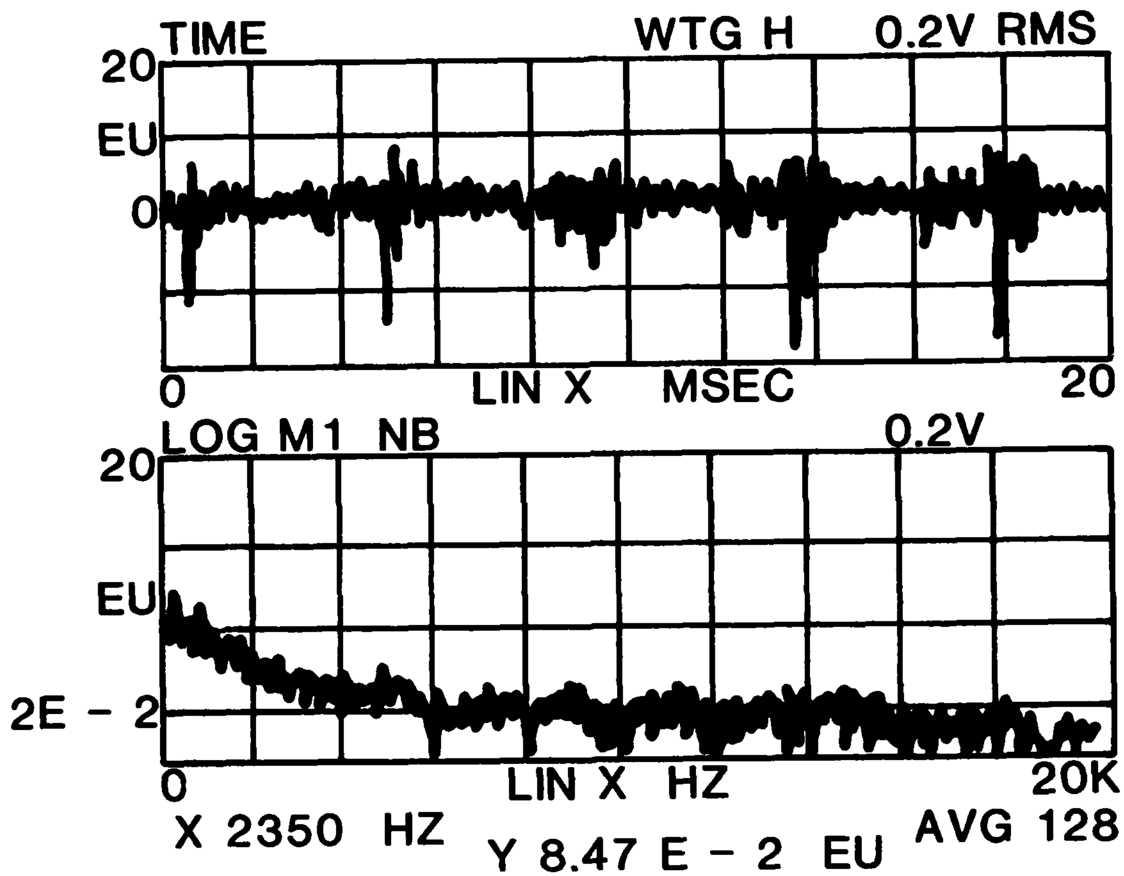

FIG. 4-1. Time-Frequency Spectrum

driven at 1200 rpm (20 Hz). A peak is expected in the pump frequency spectrum when a vane passes by the transducer. Since there are 12 vanes in the test pumps, the fundamental frequency or vane pass frequency is 240 Hz. If the fundamental frequency is given by f_0, then the first harmonic is $2f_0$, third $3f_0$ and so on. The analysis of the vane pump operating at 1200 rpm set the frequency range of investigation 0-1680 Hz to include the first seven harmonics. Therefore, accelerometers were selected to detail the frequency range of 0-2 kHz.

The signal averaging techniques applied to the input signal is an important characteristic of the diagnostic method. A real time spectrum analyzer was utilized throughout the project. "Real time" refers to the analysis capability of processing and sorting the incoming analog signal faster than it is being received by the analyzer. Inherent in real time analyzers is the processing capability of signal averaging. Signal averaging techniques reduce the noise content of the input signature and enhance the appearance of periodicities within the frequency spectrum. Signal averaging is an important parameter in the diagnostic method utilized in spectrum analysis of rotating components, such as hydraulic pumps and motors, due to its enhancement effect on the amplitudes of the periodic fundamental and corresponding harmonic components in the signature.

The display characteristics of the frequency spectrum relate to the characteristics of the waveform which are to be analyzed. This project utilized the root mean square (RMS) value of the waveform for analysis.

The RMS values can be summed on an energy basis to give an overall RMS value for a range of frequencies, or they can be used to give the amplitude of various frequency components. Analysis of the RMS value of the frequency spectrum combined with proper averaging techniques results in the most repeatable format for analyzing and comparing data. The analysis technique may vary corresponding to the test under investigation.

Obtaining a peak hold spectrum may be applied where the highest amplitude for each frequency component of the spectra is maintained, resulting in a spectrum of maximum values. This method may be applied to analysis of transient behavior as in cavitation; however, in conjunction, an RMS analysis should be made.

The diagnostic method utilized in the project for evaluating hydraulic vane pumps consisted of evaluating the RMS amplitudes of the fundamental and corresponding harmonic frequencies of the vane pass frequency. The averaging time was held constant corresponding to the necessary averages for the spectrum to remain stationary; whereas, the amplitude density distribution did not vary with time.

Facility

The test facility provided control of the various operating parameters on the component under test. It also provided the capability of collection and processing of the vibration signatures emitted from the test components.

The fluid conditioning test stand was constructed to control inlet pressure, outlet pressure, fluid temperature, pump speed, and fluid aeration level. Details of the test facility are in Appendix C.

The project promoted the development of a microprocessor test stand controller. The advantage of the controller was twofold. First, to monitor the test parameters to their preset values and, second, to initiate the development of a microprocessor for signature analysis which would be applicable in the field. Detailed descriptions of the controller and the instrumentation utilized in the project are in Appendix D.

Data Analysis Procedure

The amplitudes were analyzed for each abnormal operating mode of the pump. Two analysis methods were investigated for implementation as a diagnostic evaluation method. The baseline difference (B_D) is defined by Eq. (1)

$$B_D = A_{f_B} - A_{f_H} \qquad (1)$$

Where: A_{f_B} = *the vibration amplitude corresponding to specified harmonic frequency in the baseline signature.*

A_{f_H} = vibration amplitude corresponding to a specified harmonic frequency relating to an abnormal operating condition.

The baseline difference is a diagnostic method in which the difference in amplitudes of the harmonic frequencies between the baseline

signature and a signature representing the pump's present operating condition are compared. The other diagnostic method utilized is the <u>signature difference</u> (S_D) as defined by Eq. (2).

$$S_D = A_{f_O} - A_{f_H} \qquad (2)$$

Where: A_{f_O} = vibration amplitude corresponding the hydraulic component fundamental frequency relating to an abnormal operating condition.

A_{f_H} = vibration amplitude corresponding to a specified harmonic component of the fundamental frequency relating to an abnormal operating condition.

The signature difference is a relationship between the difference in amplitude between the vibration signature fundamental and corresponding harmonic frequencies.

The primary difference between the baseline difference and signature difference methods is in the number of acoustic traces necessary for the analysis. The baseline difference technique is based on the relationship between a permanent record of the acoustic signature of the pump when it is first put into operation (supposedly in a healthy state) and the signature of the operational (and perhaps degraded) pump. For field application, this would require the permanent storage and availability of the baseline signature of each pump.

The signature difference method, on the other hand, is based solely

on the relative amplitudes of the fundamental and corresponding harmonic components of the operating pump.

It must be noted that the proposed methods of analysis relate to a diagnostic method for rotating hydraulic components such as pumps and motors. The relationships analyze the amplitudes from the harmonic components of a frequency spectrum which can be attributed to a periodic input signal. Only rotating hydraulic equipment produces periodic characteristics in its resulting frequency spectrum. The analysis method used would not be applicable in diagnosing the operating condition of valves, for it does not possess periodic characteristics in its mechanical operation. It is proposed that a complete diagnostic unit, analyzing various components of a hydraulic system, would include a combination of diagnostic methods which will have been developed for each type of hydraulic component. The variations would consist of different frequency ranges, averaging techniques, and the characteristics of the input wave form that are to be analyzed; i.e. peak to peak, RMS, power spectral density.

The next section discusses the results in applying the two methods to operating conditions of cavitation, wear, and bearing damage utilizing accelerometer transduction. The plan of attack of the testing procedures were as follows:

1. Record the vibration signature corresponding to the baseline and

abnormal operating conditions of wear, cavitation, and damaged bearing.

2. Analyze the resulting frequency spectrum, the baseline difference, and signature difference analysis methods.
3. Evaluate the diagnostic methods for qualitative information concerning the feasibility of utilizing accelerometers as a non-intrusive diagnostic tool for application in hydraulic systems.

CHAPTER V

TEST RESULTS AND ANALYSIS

This section discusses the test results and analysis of vibration signatures corresponding to abnormal operating conditions. The acoustical signatures will be analyzed corresponding to three levels of severity of cavitation, wear, and damaged bearing. Both the baseline difference and signature difference will be presented for comparison of the two methods.

Cavitation

Cavitation is an undesirable operating condition for any hydraulic system. Cavitation of a hydraulic pump can not only decrease its operating efficiency but, through prolonged operation, can physically damage the pump. The potential for incipient failure of a hydraulic component due to cavitation leads to the desirability of its early detection.

The pump was subjected to three degrees of severity of cavitation. The first degree of cavitation severity was defined as a slight cavitation which can hardly be heard by human ears. The second degree was a cavitation which can be heard by human ears if attention is directed to it. The third degree was a heavy cavitation which can be readily heard without attention. The degree of cavitation was controlled by two parameters; pump inlet pressure and the fluid aeration level. The pump inlet pressure was used as a catalyst to increase the bubble formation in the fluid

at the inlet of the pump. As the inlet pressure was decreased, the severity of cavitation increased accordingly, due to the increase in air bubbles entering the pumping chamber. The aeration level acts as a "sink" from which the air bubbles form. The control of the aeration level was to enhance the repeatability of the severity levels throughout the cavitation test.

Fig. 5-1 is a representation of the vibration signature for the first seven harmonics resulting from the three different severity levels of cavitation. The figure shows an actual decrease in the vibration amplitude throughout the first level of severity. This indicated that the inlet pressure at the first degree of severity is above the incipient pressure corresponding to the operating conditions of the pump.

Incipient pressure is defined as the pressure at which the release of entrained air cushions the effect of the resulting cavitation. Maroney [2] found similar results from cavitation tests where the sound pressure level of a hydraulic gear pump actually decreased as the cavitation level increased until it reached an incipient pressure.

The analysis methods applied to the cavitation situation are shown in Figs. 5-2 and 5-3. Fig. 5-2 shows the baseline difference analysis, and Fig. 5-3 shows the signature difference analysis. For the detection of cavitation situation, the baseline difference, Fig. 5-2, lacks consistency; however, the signature difference analysis offers a clear

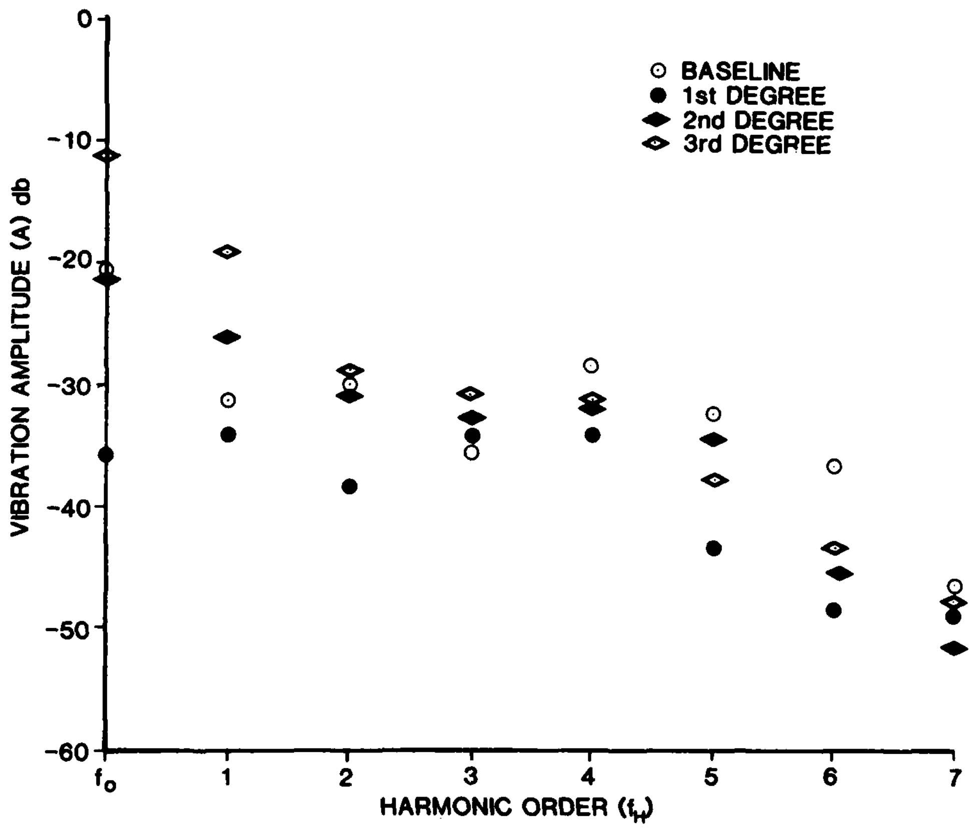

FIG. 5-1. Cavitation - Vibration Amplitude vs Harmonic Order

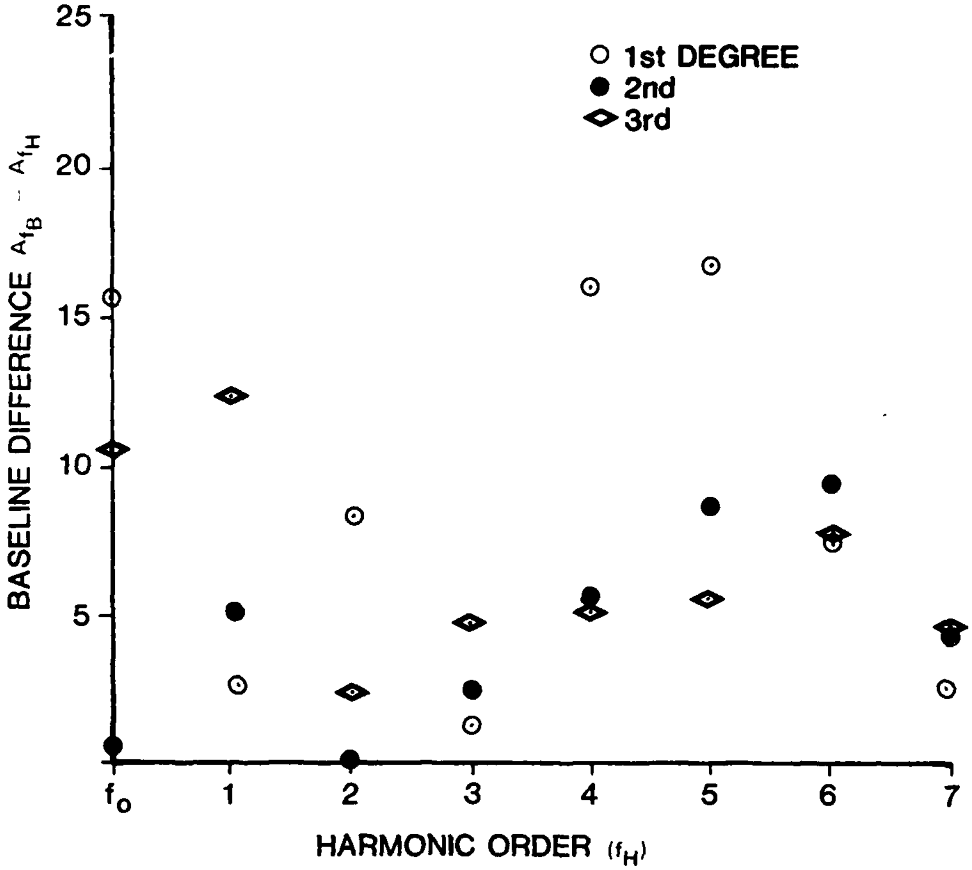

FIG. 5-2. Cavitation Baseline Difference vs Harmonic Order

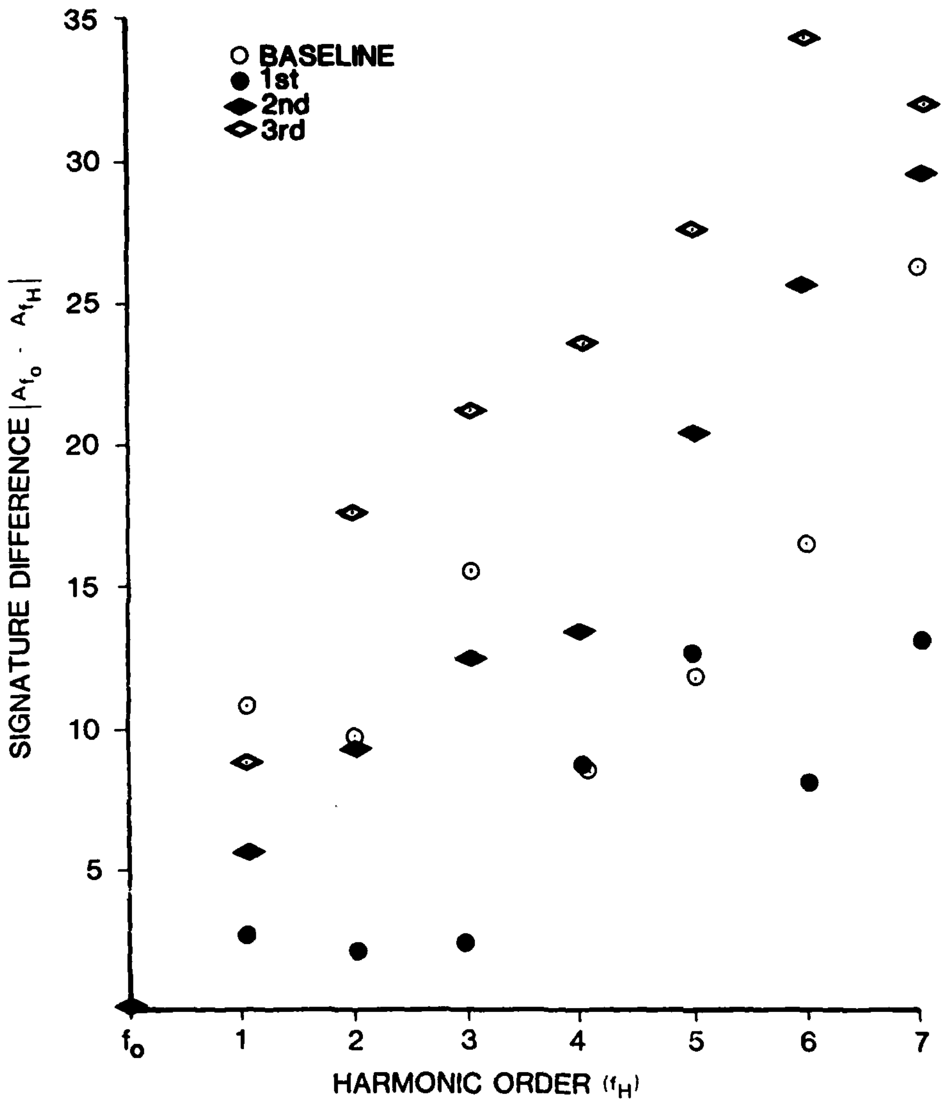

FIG. 5-3. Cavitation Signature Difference vs Harmonic Order

tendency for cavitation severity. The signature differences above the fifth harmonic show the severity. Especially, the signature difference at the sixth harmonic distinguishes the cavitation severity clearly.

Wear

Wear is a common replacement criterion for hydraulic components. The flow degradation associated with a worn hydraulic pump severely decreases the efficiency of the entire hydraulic system. The degradation associated with a worn pump can be related to decrease in volumetric efficiency, which in turn can be attributed to the increased leakage paths and clearances associated with internally worn parts.

Theoretically, the wear (in this case intentionally induced by running the pump with fluid contaminated with AC Fine Test Dust) should alter the vibration signature of the pump. The tests were to analyze whether these changes could be detected by conventional accelerometers.

Fig. 5-4 represents the amplitude levels of the first seven harmonics. The amplitude variations corresponding to three levels of flow degradation (10, 20, and 30 percent) were analyzed by both methods. The baseline difference and signature difference are shown in Figs. 5-5 and 5-6, respectively.

Both methods showed a good correlation with a degree of flow degradation at seventh harmonic; however, a good correlation could not be

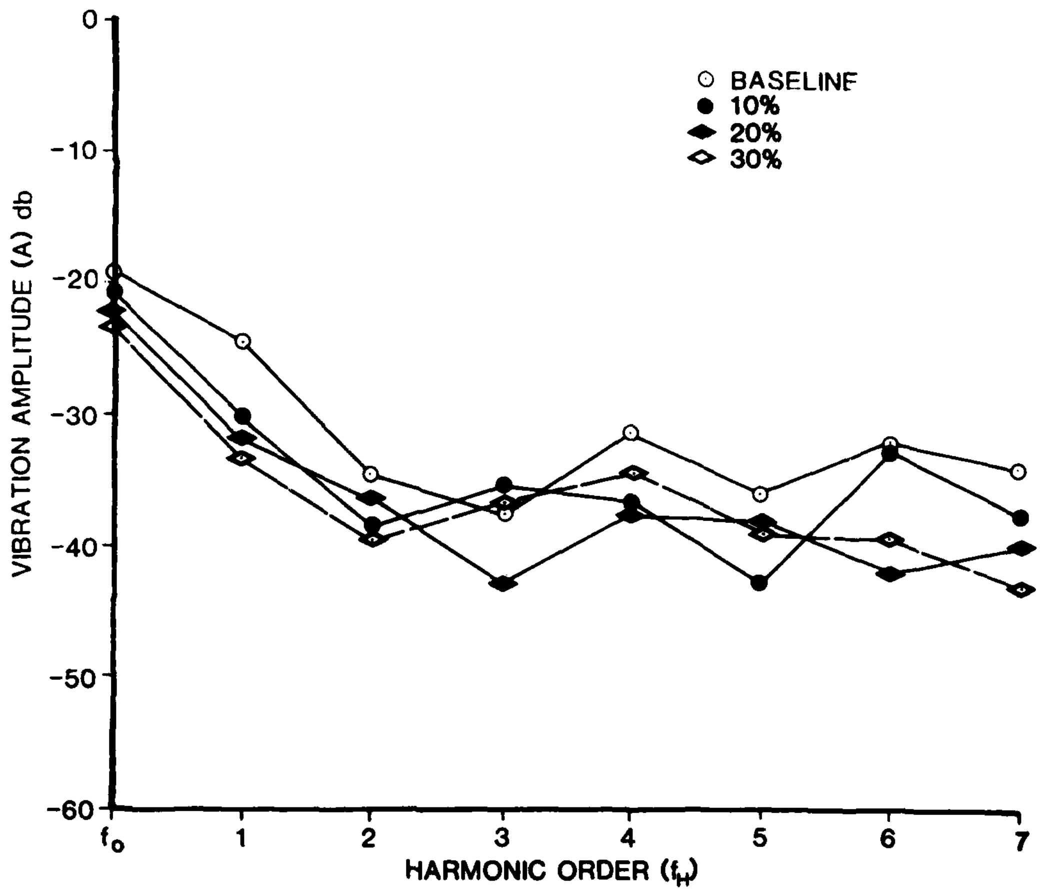

FIG. 5-4. Wear Vibration Amplitude vs Harmonic Order

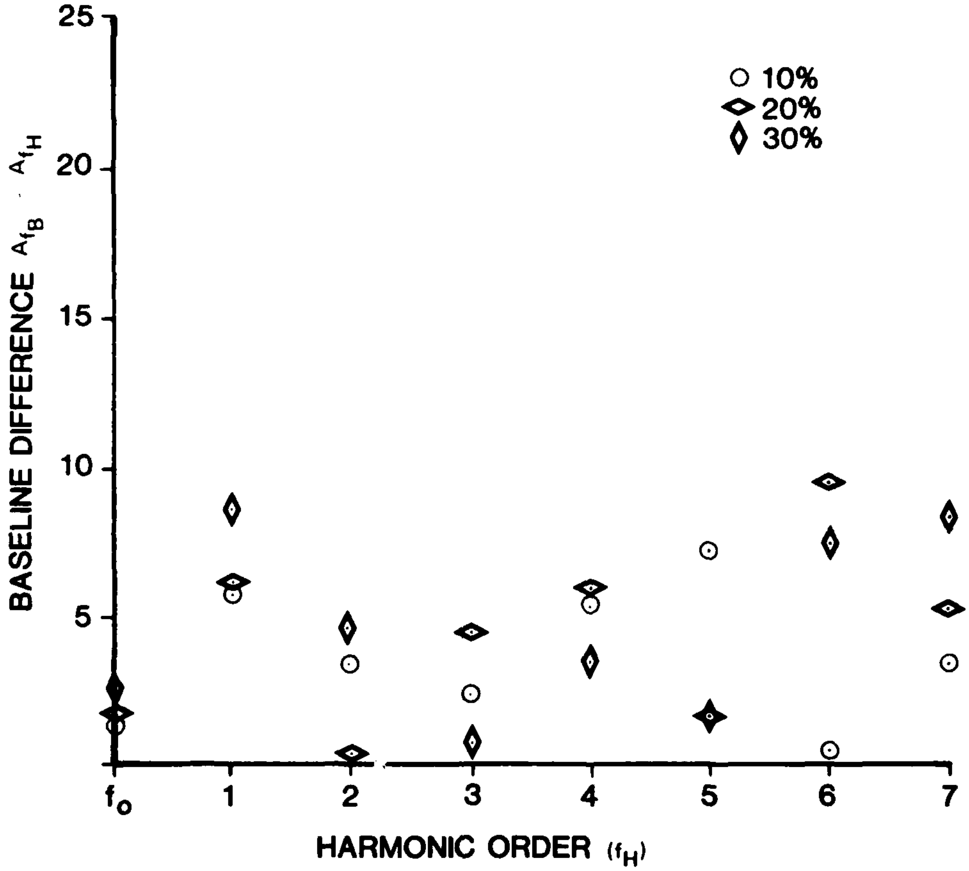

FIG. 5-5. Wear Baseline Difference vs Harmonic Order

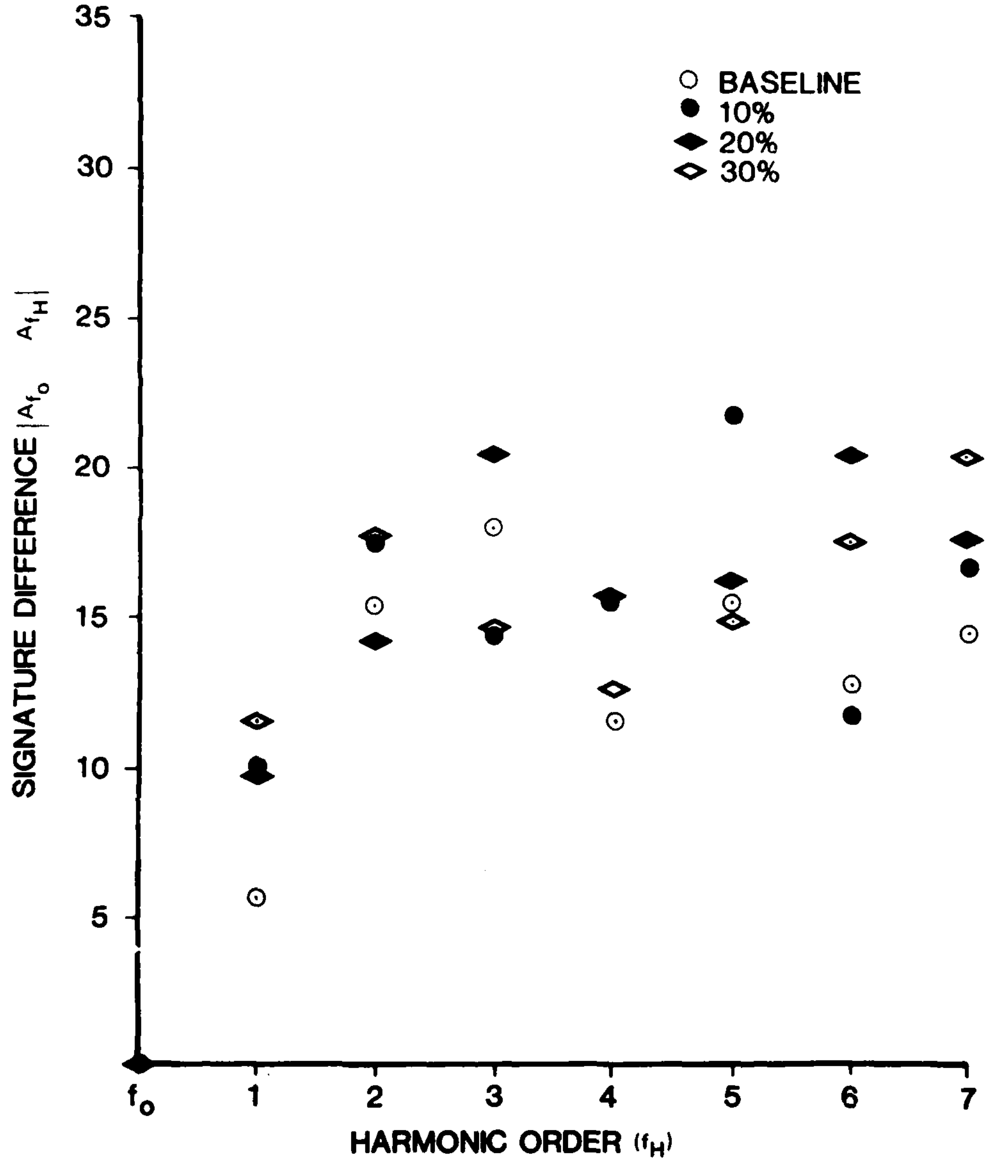

FIG. 5-6. Wear Signature Difference vs Harmonic Order

obtained at lower harmonics. This situation can be endorsed by the following consideration. The acoustic signal which is altered due to the flow degradation is a leakage flow noise across the component. The noise created by the leakage flow mainly contains high frequency signatures. Hence, the degree of flow degradation can be better detected at higher harmonic frequencies.

Bearing Damage

Analysis of bearings using vibration analysis of rotating machinery has been utilized successfully by industry for some time. Signature analysis of bearings can provide information concerning the specific location and severity of the defect. The procedure utilized requires a highly trained technician to evaluate and interpret the signature. It was not the intent of this project to "re-invent the wheel." The scope of the test was to evaluate the resulting signature from a damaged bearing and see if it could be detected from either of the two methods and thus require no human interface.

The pumps utilized sealed, roller, non-friction bearings. The system consisted of seven roller bearings in which one was scored for test purposes. The vibration amplitudes are shown in Fig. 5-7. The baseline and signature difference methods are shown in Figs. 5-8 and 5-9, respectively. Since there was only one bearing damage situation introduced to the test pump, it is not possible to discuss a trend of the baseline differences; however, the baseline difference itself can be

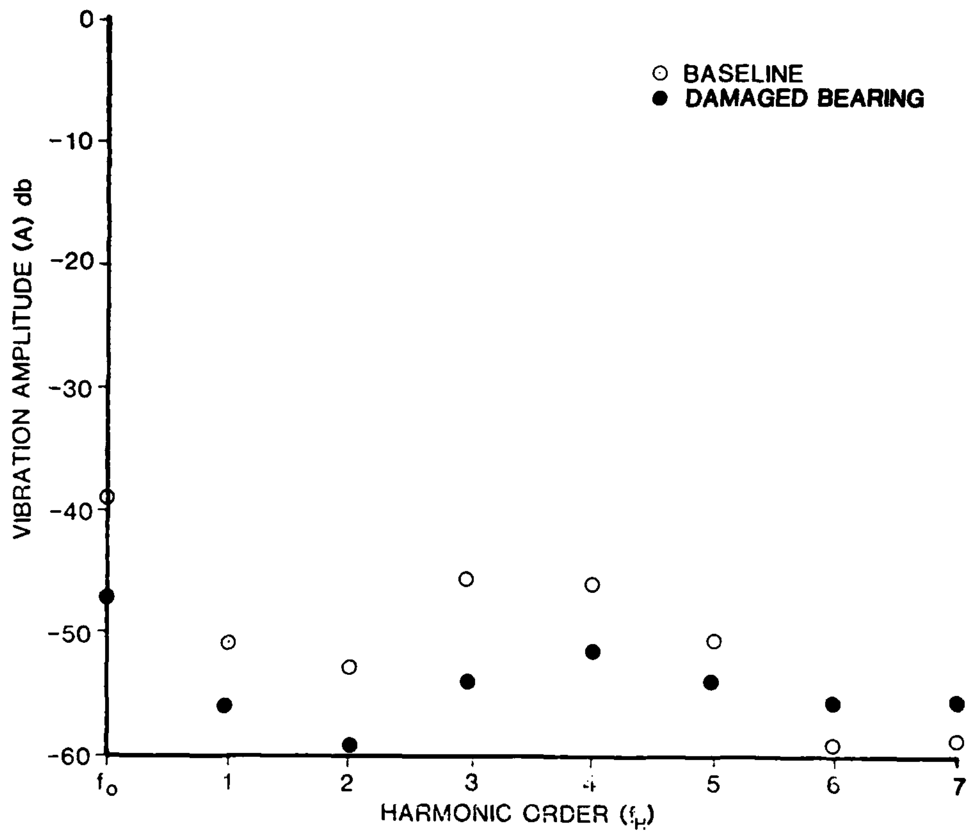

FIG. 5-7. Bearing Damage Vibration vs Harmonic Order

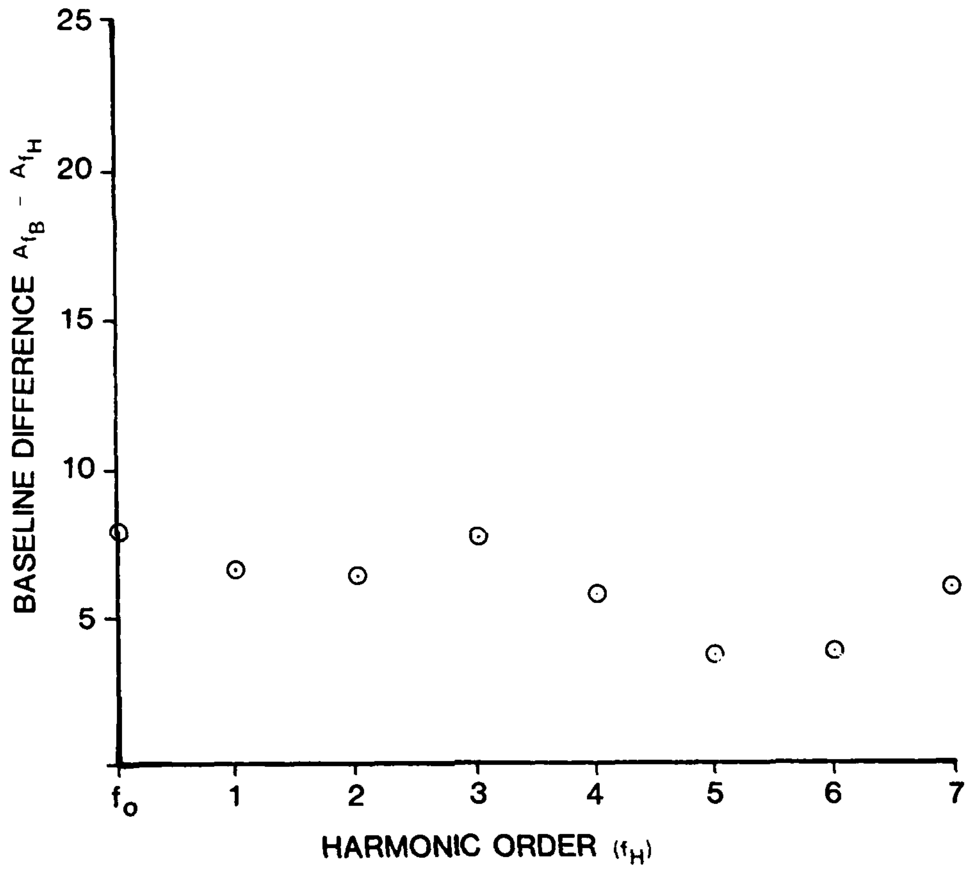

FIG. 5-8. Bearing Damage Baseline Difference vs Harmonic Order

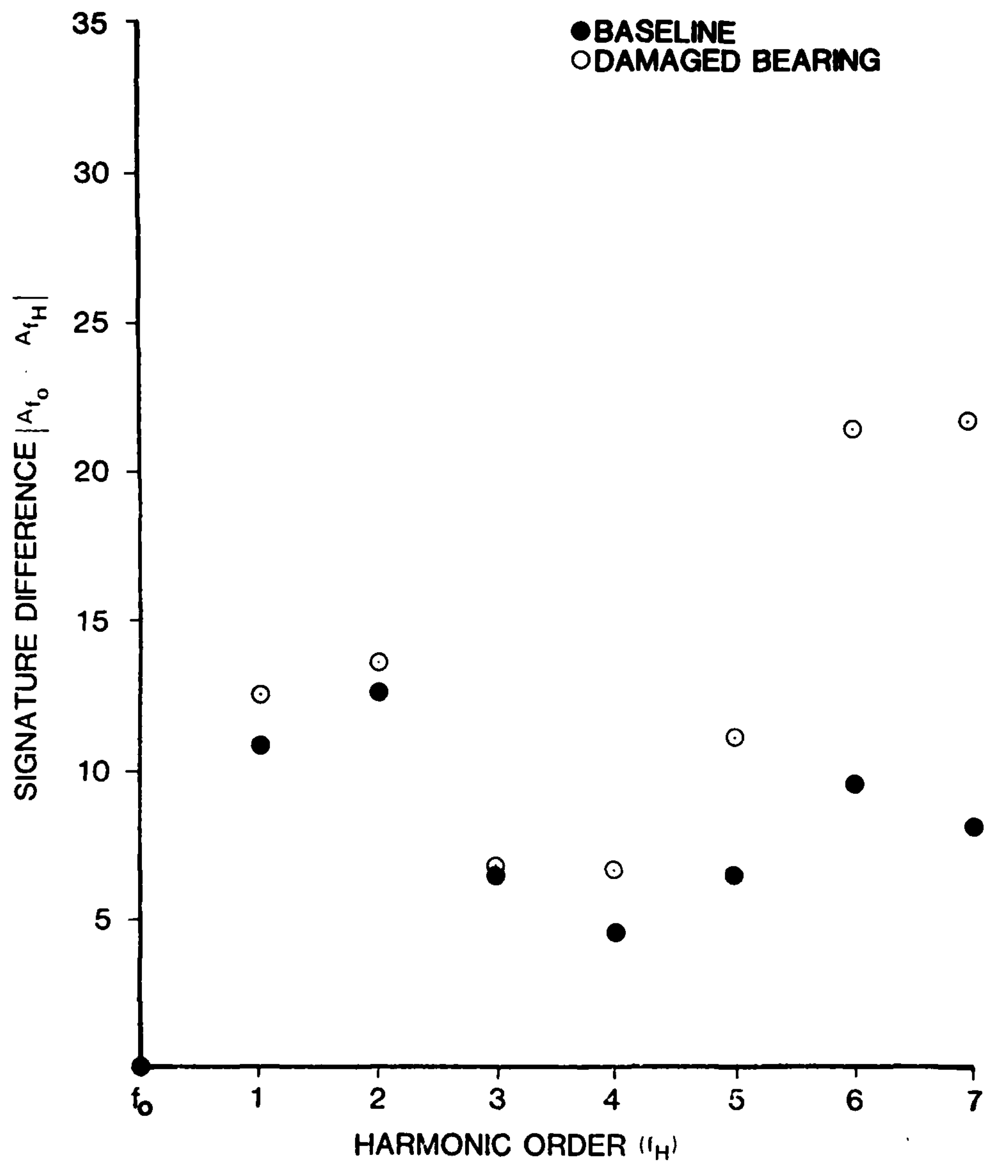

FIG. 5-9. Bearing Damage Signature Difference vs Harmonic Order

an indication of the damage. The signature difference in Fig. 5-9 shows some promising results at the higher frequencies; namely, the sixth and seventh harmonics. Due to the characteristics concerning the construction of the bearing assemblies of hydraulic pumps, they are replaced and not repaired; thus, the limits set down by an analysis method concerning bearing damage represent a go/no-go decision concerning the pump's mechanical integrity.

Result Summary

From the analyses of the test results, the capability of the acoustical diagnostic method can be summarized as shown in Table 5-1. The signature difference demonstrated a better potential as a non-intrusive diagnostic method. The analyses of the test results indicate that the higher frequencies offer important information for the detection of failures.

Table 5-1. Test Result Summary

Failure Mode	Baseline Difference	Signature Difference
Cavitation	Not applicable	Increase at 6th and 7th harmonics
Wear (Flow Degradation)	Increase at 7th harmonic	Increase at 7th harmonic
Bearing Damage	Increase at all harmonics	Increase at 6th and 7th harmonics

Further Investigation

Cavitation can be related to the "popping" associated with bubble collapse, which can be considered a random high frequency phenomena. Wear experienced by a pump is related to the leakage or backflow corresponding to the increased clearances between the contacting surfaces. This leakage contributes a high frequency characteristic to the pump's overall vibration signature. The significance of the higher frequencies lead to an investigative test. The initial testing considered of analyzing a frequency range from 0-2 kHz. The frequency range was expended to 20 kHz on a hydraulic vane pump operating with a damaged vane. The resulting frequency spectrum as seen on the spectrum analyzer is shown in Fig. 5-10.

Several peaks can be observed on the spectrum. Generally, increasing the frequency range decreases the resolution capability of the analysis; however, commercially available analyzers, through translation techniques, maintain the necessary resolution at the expense of increasing the analysis rate. The technique is illustrated in Fig. 5-11. The spectrum peak at 10550 Hz in Fig. 5-10 is analyzed in Fig. 5-11. This method illustrates the capability of investigating higher frequencies as a potential diagnostic method. The methods applied at the lower frequencies consisted of harmonic analysis. When analyzing higher frequencies, waveform analysis, such as RMS power summations over a specified range of frequencies, could prove to be a very powerful diagnostic tool. The higher frequencies will be of major concern when analyzing the frequency characteristics of non-rotating components such as valves and cylinders.

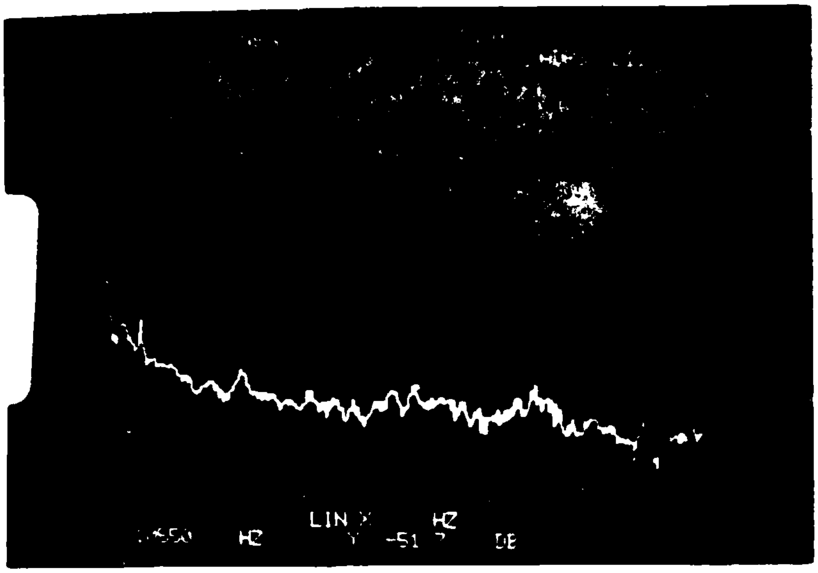

FIG. 5-10. Vane Pump Frequency Spectrum

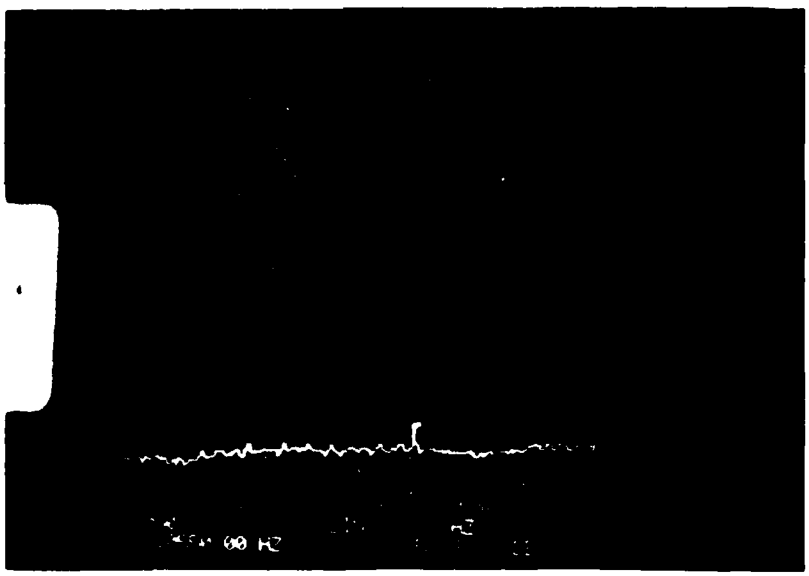

Fig. 5-11. Vane Pump Frequency Spectrum—Translated

Accelerometers usually have upper frequency ranges in the order of 40 kHz; however, some piezoelectric devices can measure frequencies in the order of 100 kHz. The higher frequencies combined with various signature analysis techniques may be the key to the development of a complete diagnostic analysis system.

The development of a non-intrusive diagnostic method would consist of an analysis technique which would involve a minimal amount of human interface for the diagnostic evaluation of the vibration signature. The diagnostic method to be utilized including frequency range and the waveform analysis technique would be part of a dedicated software program used in a microprocessor spectrum analyzer. Fig. 5-12 illustrates a flow chart that would accompany the signature difference analysis method used in Figs. 5-3, 5-6, and 5-9. A large transition exists from the test results of the project and Fig. 5-12; however, this serves to illustrate the ideology behind the proposed diagnostic method. The parameters to be entered into the analysis program would consist of values of the signature difference and corresponding harmonics which would set vibrational setpoints from which to compare the vibrational amplitudes of hydraulic components in service. The setpoints would represent limit values in relation to the incoming signal for values of wear, cavitation, or damaged bearings.

A complete diagnostic system would consist of several such subroutines corresponding to various failure modes and the types of component under test.

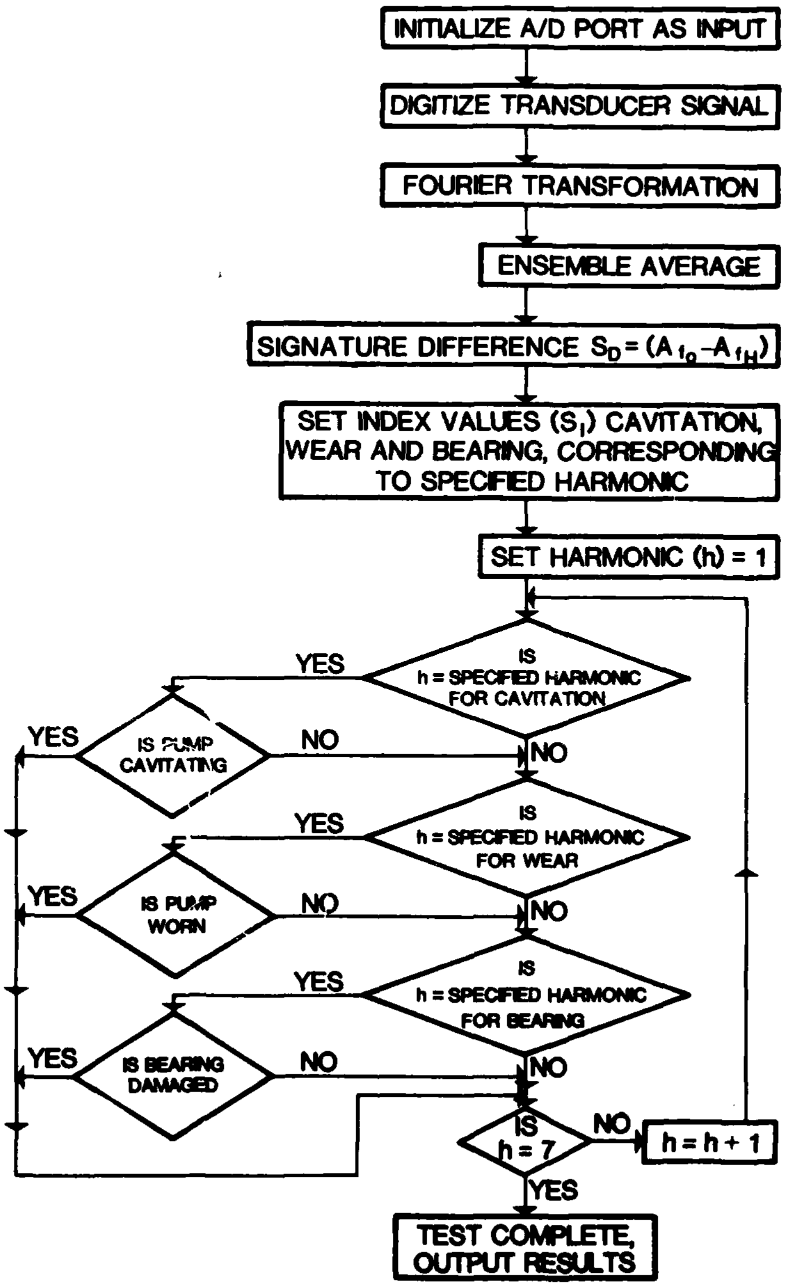

FIG. 5-12. Logic Chart

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the results of the project:

1. Transducer verification tests were completed comparing microphone and accelerometer methods to be used as a non-intrusive diagnostic tool. Both methods produced distinguishable differences in their signatures corresponding to operating conditions of cavitation and vane damage.
2. The structureborne noise was selected for use in further development of the diagnostic method because its test results showed better consistency on all harmonics and it has fewer environmental limitations.
3. Cavitation can be detected by the signature difference analysis method. The degree of cavitation severity was best indicated by 6th and 7th harmonics.
4. Wear damage which leads to the flow degradation can be detected by both the baseline and signature differences. The 7th harmonic gave information on wear severity.
5. Bearing damage of the test vane pump can be found by increases in the 6th and 7th harmonics of the signature difference.
6. It was found as a result of the tests that higher frequencies give important information to detect failures on hydraulic components.

The following recommendations are made:

1. The program is in the early stage of development; therefore, other analysis techniques should be investigated.
2. The frequency range of investigation should be expanded to account for the high frequency contributions. For example, the frequency range of 0-100 kHz should be investigated utilizing various analysis techniques to define the most accurate diagnostic technique.
3. Testing should investigate the effect on the vibration signature in response to small and large variations in the system's operating parameters of temperature, pressure, aeration level, speed, and level of contamination.
4. Investigation and verification tests will be necessary for the diagnostic method to detect two or three different types of failures occuring at the same time.

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2. Maroney, G. E., "Acoustical Signature Analysis of High Pressure Fluid Pumping Phenomena," Doctoral Dissertation, Oklahoma State University, Stillwater, Okla., 1976.

3. Iwanaga, M., and K. H. Tsai, "Hydraulic Reservoir Design—Part 1: Sloped Screen Configuration," The BFPR Journal, 1980, pp. 209-215.

4. Nipper, M. A., "Adapting Commercially Available Computer for Process Control," The BFPR Journal, 1981, pp. 393-398.

APPENDIX A

DETAILS OF PUMP BREAK-IN

The break-in procedure utilized in the project followed the manufacturer's guidelines.

The high wear rate during the break-in period is partially due to surface roughness being worn from the original profile of the internal interfaces of the pump. The pressure increments during the break-in period are to gradually load the pump, resulting in a more uniform wear of the internal interfaces. A test was run to verify a constant baseline signature of the pump prior to break-in. This was important for purposes of comparing the data as in the baseline index. Similarities in the baseline signature are important. A test was run to verify the information of the baseline signature during break-in and to evaluate the manufacturer's proposed break-in procedure.

Break-In Evaluation

Background

Since break-in periods are associated with high wear rates, ferrographic oil analyses were conducted at regular intervals during the break-in period. A correlation was made between the ferrographic density readings and the formation of the pump's baseline signature. The anticipated results would yield a simultaneous decrease in the amount of wear particles exhibited from the ferrographic analysis, as the pump signature stabilized.

Break-In Procedure

1. Operate the pump at the manufacturer's recommended operating conditions during break-in.
2. Take ferrographic oil samples every 5 minutes throughout the duration of the break-in period.
3. Record the vibration signature at 15-min intervals corresponding to the pressure increase associated with the break-in period.

Analysis

The overall root mean square (RMS) value of sound pressure levels was evaluated from 0-2 kHz including the first seven harmonics of the fundamental vane pass frequency. The RMS value corresponding to each pressure interval was divided by the RMS of the baseline signature, as developed after 3 hours of operation. The results are plotted in Fig. A-1. It can be seen that the formation of the baseline is approximately complete following 45 minutes of operation. The results of the ferrographic analysis are plotted in Fig. A-2. The ferrographic analysis provides information concerning the amount of wear particles contained in a given oil sample. The figure indicates that the particle density decreased rapidly through the first 15 minutes of operation. It continued to decline to a steady value throughout approximately 45 minutes of operation. There is good correlation between Figs. A-1 and A-2, indicating the wear associated with break-in is complete after 45 minutes of operation. This is consistent with the analysis of the vibration signature.

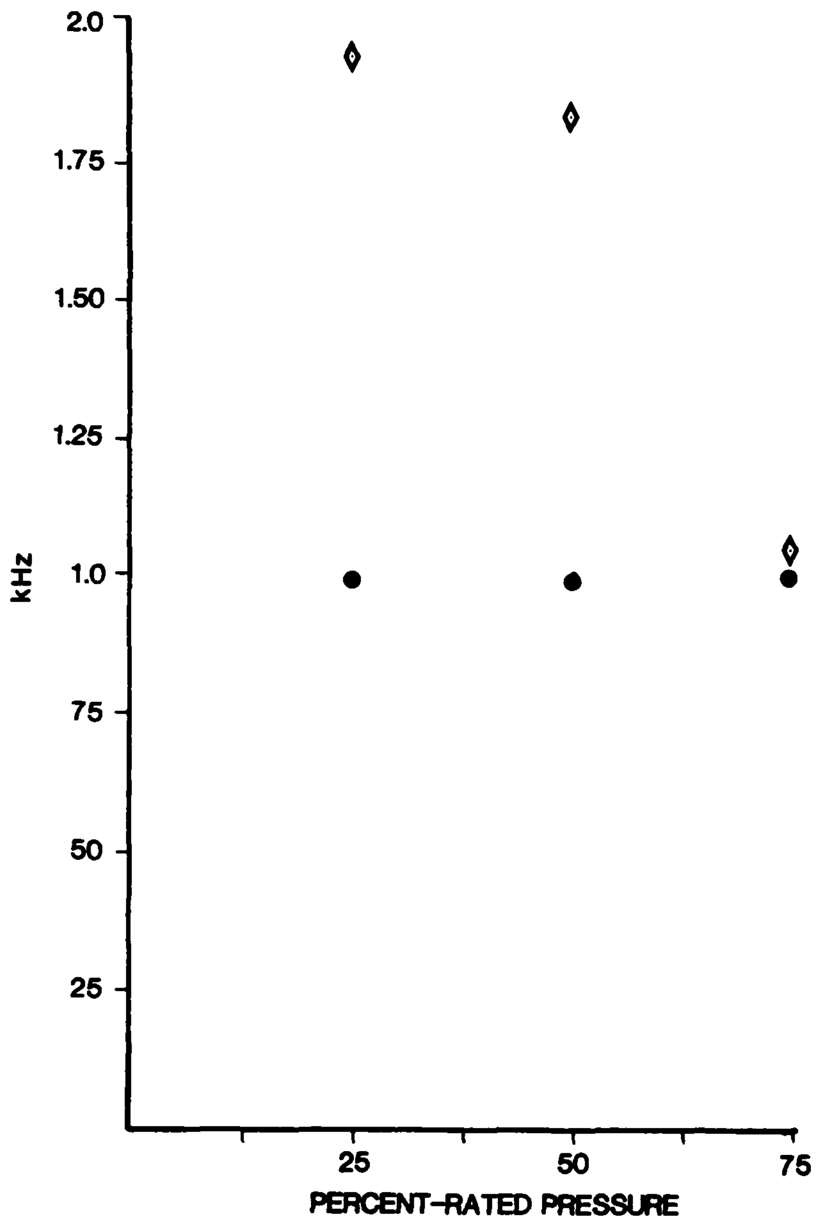


FIG. A-1. Non-Intrusive Diagnostics Break-In Procedure

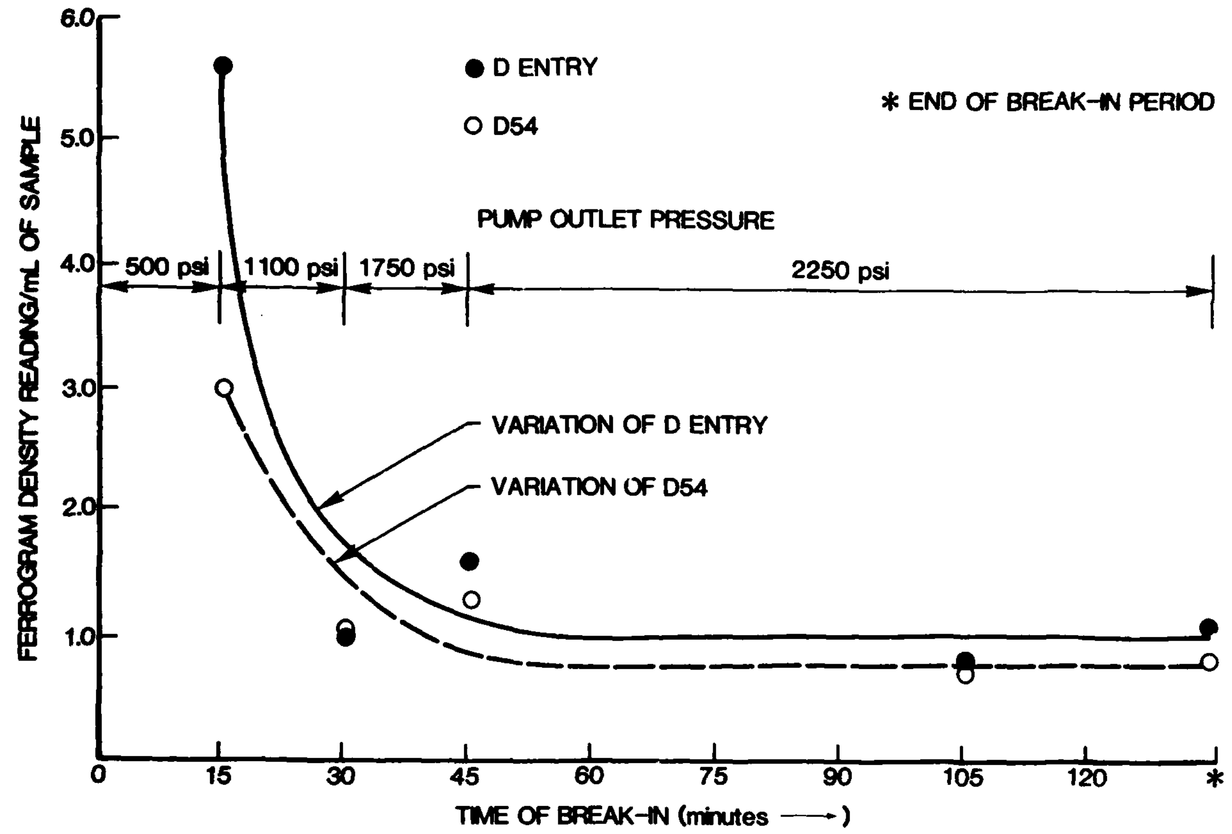


FIG. A-2. Ferrographic Analysis in Pump Break-in

Summary

The analysis verified the manufacturer's break-in procedure. The break-in procedure was utilized throughout the project for establishing the baseline signature for each pump.

It is recommended in the development of a non-intrusive diagnostic technique that the effect of various break-in procedures on the resulting baseline signature of a hydraulic pump be evaluated.

APPENDIX B

DIAGNOSTIC TEST PROCEDURES AND OPERATING CONDITION

Test Procedures

Each test consisted of Basic Operating Procedures. These procedures were to insure consistent operating conditions which could be repeated for any given test.

Basic Operating Procedures for Tests:

1. Each pump which was disassembled to implant defective components was reassembled to the factory specified torque. Each pump was mounted on the test block with a torque of 50 NM to insure that the structural vibration was consistent throughout each test.
2. Each pump was subjected to the break-in procedure as set down by the manufacturer for the particular pump.
3. Preceding break-in, the test operating conditions of temperature and pressure were maintained at steady state for 1.0 hour, prior to the acquisition of the baseline signature.
4. Prior to the data acquisition of any given test, the system aeration level was measured. The level was kept at less than 1.0 percent except during cavitation tests.
5. The instrumentation was subjected to a warmup period of no less than 45 minutes prior to each test.
6. The transducers were calibrated according the manufacturer's procedures.

TEST OPERATION CONDITIONS

CAVITATION TEST	Number TH-DVT-002
Shaft Speed	1200 RPM
Pump Inlet Pressure	6.0 PSIG
Pump Discharge Pressure	2250 PSIG
Hydraulic Fluid	MIL-L-2104
Fluid Temperature	$150^{o}F$
Flow Rate	6.4 GPM
Aeration Level	Controlled to maintain specific cavitation severities

WEAR TEST	Number TH-WCT-005
Shaft Speed	1200 RPM
Pump Inlet Pressure	6.0 PSIG
Pump Discharge Pressure	2250 PSIG
Hydraulic Fluid	MIL-L-2104
Fluid Temperature	$150^{o}F$
Flow Rate	6.2 GPM
Aeration Level	less than 1.0%

DAMAGED BEARING TEST	Number TH-BND-006
Shaft Speed	1200 RPM
Pump Inlet Pressure	6.0 PSIG
Pump Discharge Pressure	2250 PSIG
Hydraulic Fluid	MIL-L-2104
Fluid Temperature	$150^{o}F$
Flow Rate	6.3 GPM
Aeration Level	less than 1.0%

APPENDIX C

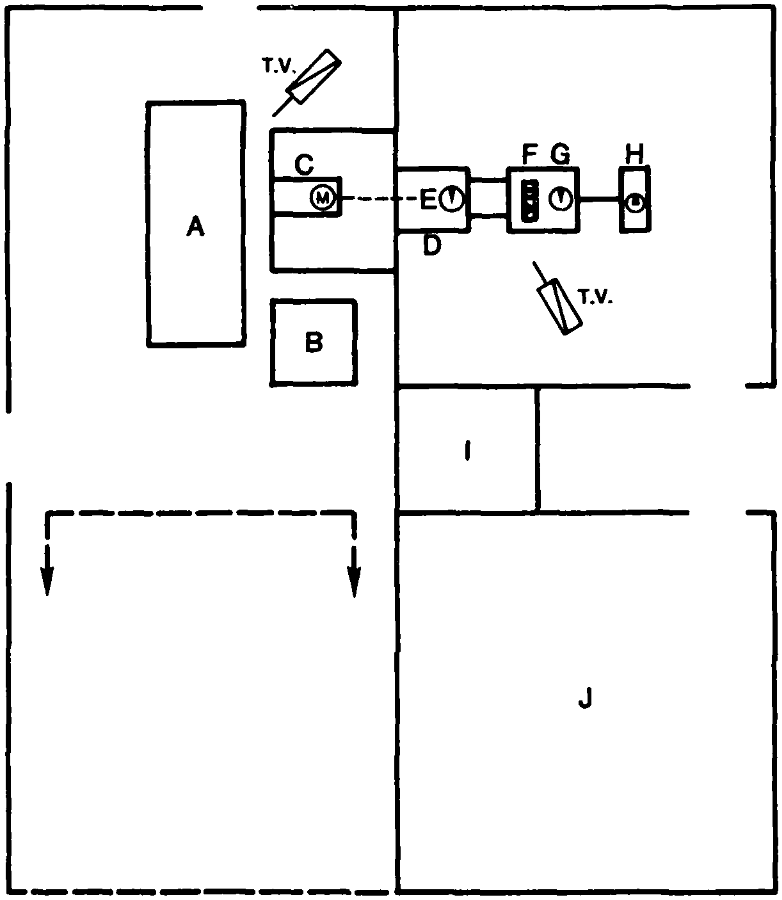
TEST FACILITY

The acoustic facility at the Fluid Power Research Center was developed to meet the test requirements throughout all phases of the project. The test system was designed to facilitate all phases of a testing program towards the development of a non-intrusive diagnostic field package. The layout of the facility, which occupies 1400 sq. ft. of the FPRC, is shown in Fig. C-1. The facility can be subdivided into three areas: test cell, reverberant room, and instrumentation lab.

The test cell consists of the primary and secondary fluid conditioning system, drive system, and the contaminant sensitivity test stand. These systems are located outside of the reverberant room so as to not interfere with the acoustic measurements. The reverberant room is an acoustically reflective environment which includes the test circuit. The test circuit accommodates the test components--hydraulic pumps, motor, and valves. The instrumentation lab contains signature analysis measurement equipment. The computer test stand controller located in the instrumentation lab provides full control of all systems during a test. The entire test, including the data acquisition, is operated from the instrumentation lab. The closed circuit T.V. cameras provide visual inspection of operating equipment during tests.

Primary Fluid Conditioning Test Stand

The primary fluid conditioning test stand, Figs. C-2a and C-2b, was



A) PRIM. FLUID-COND.
B) SEC. FLUID-COND.
C) DRIVING MOTOR
D) MOUNTING BLOCK
E) TEST PUMP
F) TEST VALVE
G) TEST MOTOR
H) LOAD PUMP
I) INSTRUMENTATION
J) OFFICE

FIG. C-1. Test Facility

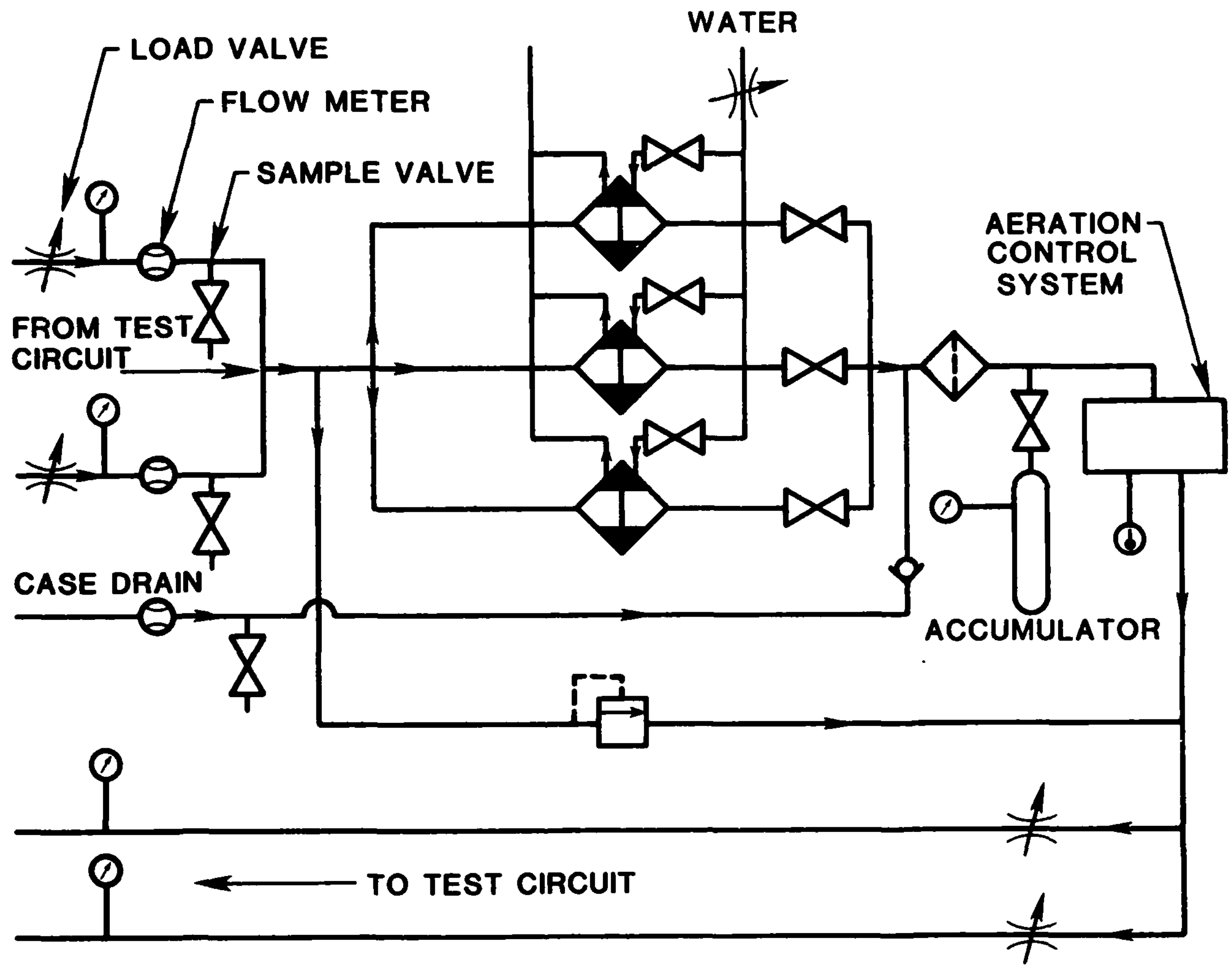


FIG. C-2a. Aeration Control Test Stand

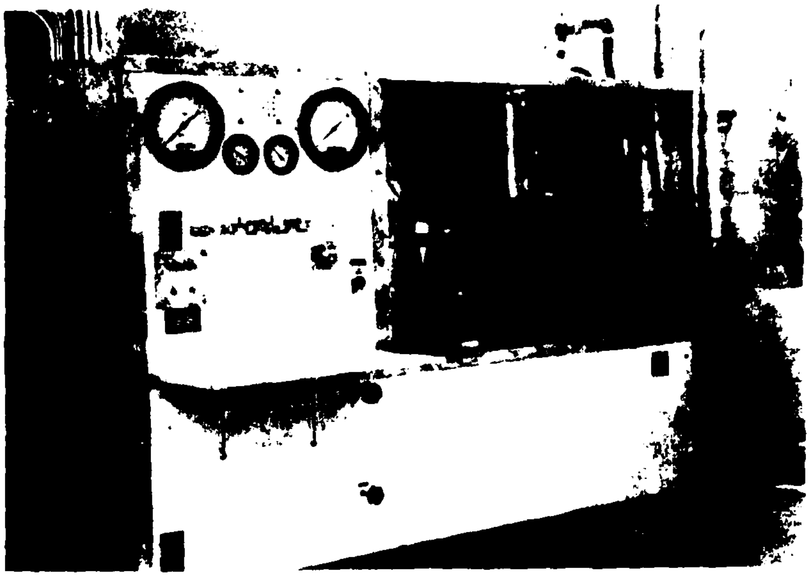


FIG. C-2b. Fluid Conditioning Stand

FIG. C-3. Air Injecting and Mixing Vessel

constructed during the contract to provide the operating test conditions. The inlet pressure, discharge pressure, fluid temperature, and aeration level were maintained to a steady state prior to the recording of data. The parameters can be controlled both manually or automatically. The test stand is interfaced into a test stand controller for automatic monitoring of the operating parameters.

Aeration Levels

The primary fluid conditioning system provided control of the fluid aeration level. The system consists of aeration (air injection), aeration measurement, and deaeration (air removal) equipment. The tests, excluding cavitation, were operated under a constant aeration level. Air injection is provided through the air injecting vessel and the mixing vessel as shown in Fig. C-3. Air is injected into the injection chamber to a specified pressure. The air in the injection chamber is then injected into the mixing chamber. The amount of air injected into the mixing chamber is proportional to the pressure drop in the injection chamber based on the ideal gas equation of state. The air and oil in the mixing chamber, in predetermined proportions, is then added to the system fluid.

The deaeration system consists of the mixing vessel and the system reservoir. The system fluid passes through the mixing chamber, which can be subjected to a vacuum. The slight vacuum in the mixing chamber acts to withdraw the air from the oil. The reservoir was designed with air removal capabilities. The reservoir utilized the slope screen method

proposed by Iwanaga [3] for air bubble removal. The reservoir is shown in Fig. C-2b. The reservoir utilizes an incline wire mesh screen to trap the air bubbles which are in the fluid. The reservoir is bypassed during aeration. The system provides approximate quantitative monitoring and control of the fluid aeration level.

The drive system is located in the test cell. It consists of a 250 HP variable speed motor which is coupled to the test pump through belt drives. The system provides the capability of operating test components accurately over a wide range of speed.

The test system utilized in the FPRC pump contamination sensitivity test was designed to maintain the controlled amount of test contaminants which were introduced to the test pumps. A schematic of the system is shown in Fig. C-4. The contaminants were injected to specifications into the fluid. The system is manually operated and monitors all the operating test parameters.

The test components were operated in the reverberant room as shown in Fig. C-5. The test pump was mounted on a cement block to stabilize the vibration resulting from the drive shaft. The pump is mounted directly on an aluminum mounting block. The block eliminated the effects of lateral vibration. The rigidity of the mounting block insured that the vibration signature from the pump was not a result of outside force excitations.

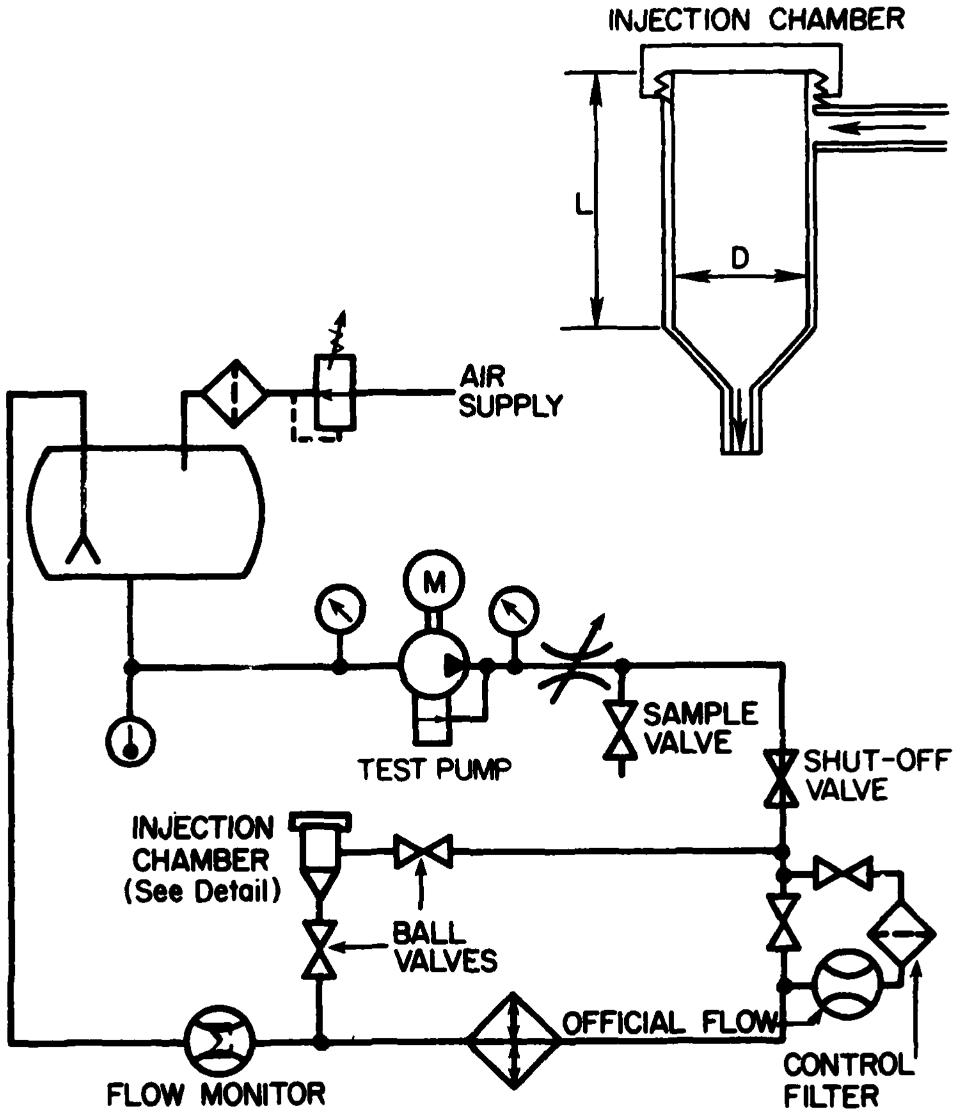


FIG. C-4. Typical Pump Contaminant Sensitivity Test Circuit

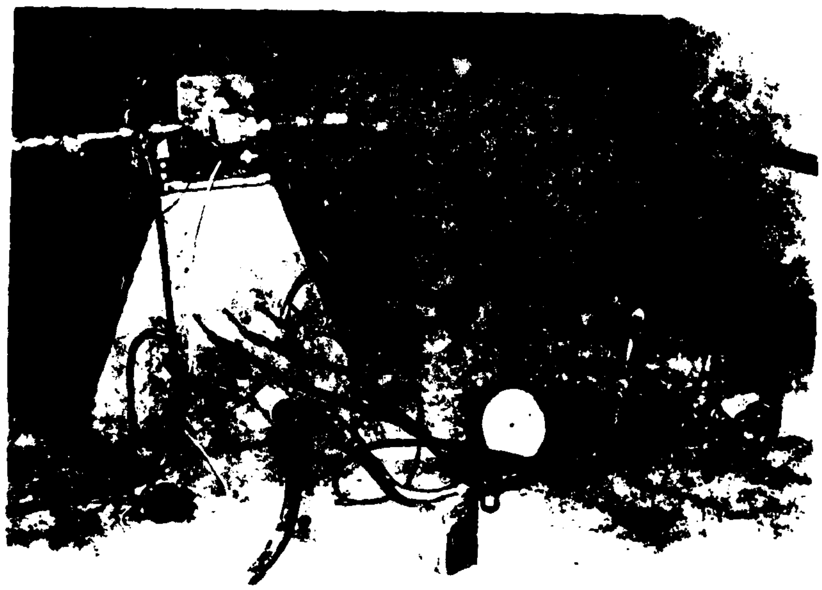


FIG. C-5 Pump Operation in the Reverberent Room

The test facility utilized a reverberant room. Reverberant rooms are acoustically reflective environments which negate the location effect of the transducer (microphone). The room contained rotating vanes to break up standing wave patterns within the room. Standing waves create nodes (sound levels of high intensity) and antinodes (low intensity). The reverberant room was utilized for the measurement of the total acoustic power of a source whose sound energy is distributed over a wide band of frequencies.

The facility provides the necessary equipment and instrumentation to carry out a wide variety of tests, including both structureborne and airborne measurements.

APPENDIX D

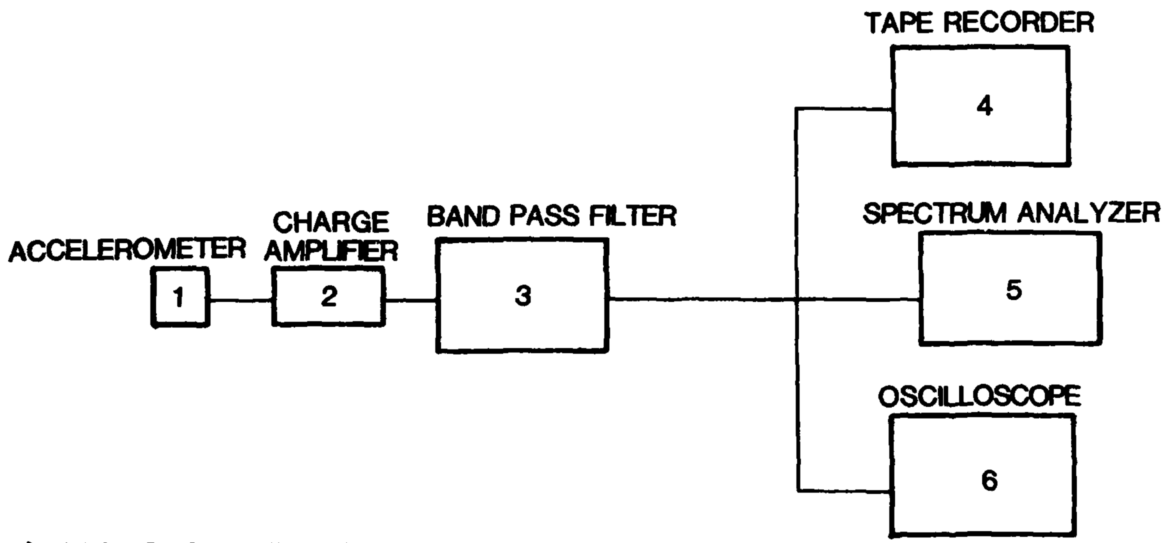
TEST STAND CONTROLLER

The test stand controller shown in Fig. D-1 continuously monitored testing and maintained all operating conditions to their preset values. At the onset of each test, the desired operating conditions were entered into the program as setpoints. Once the setpoints were entered, the computer would bring the test system to a steady state operating condition corresponding to the preset values. The operating conditions of the test stand which were monitored by the computer included pump inlet pressure, fluid temperatures, RPM, and flow rate.

The test controller provided visual inspection of the test pump and test stand through two T.V. cameras. It provided full control of both hydraulic and pneumatic systems through operation of 18 solenoid valves. The software contained emergency shutdown procedures through a continuous monitoring of the test. The controller had a visual display which was a continuous record of the test stand's operating status.

A commercially available TRS-80 microcomputer was used for the test stand controller [4]. The human interface and mass storage blocks were developed at the FPRC.

Complete technical information including system schematics can be obtained for the TRS-80, allowing system modification and repairs to be performed by the system designer. The total cost of the TRS-80 system



1) ACCELEROMETER: BBM 507
2) CHARGE AMPLIFIER: BBM P18
3) ACTIVE FILTER: MULTIMETRICS AF-420
4) TAPE RECORDER: TBAC 1230
5) SPECTRUM ANALYZER: SPECTRAL DYNAMICS SD-345
6) OSCILLOSCOPE: NICOLET 2090

FIG. D-1. Instrumentation System

was approximately $750.

The standard (STD) card rack system was selected for the control interface between the TRS-80 and the vibration diagnostic test system (VDTS). By obtaining a TRS-80-to-STD bus interface card, the TRS-80 has full control of the STD bus through a ribbon cable interconnection.

The VDTS has several analog parameters that must be monitored and controlled. For this purposed, a STD analog-to-digital (A/D) converter card was obtained. The STD A/D card offers 32 separate input channels through which pressure and temperature signals can be measured. The additional input channels add to the expandability of the system.

The computer controller for the VDTS also had to have the capabilities to monitor switch closures, control AC and DC relays, and update an LED matrix status indicator. A 64-channel STD digital input/output board was selected to perform these functions.

To facilitate communications between the TRS-80 and a line printer, a serial data interface card was selected. This card also has the capabilities to allow for modern communication between the TRS-80 and the University's IBM computer, should this feature be needed in the future.

To allow for simplicity in interfacing the computer to the AC and DC relays, optically isolated solid state relay racks were used for the

VDTS. This type of relay rack allows 16 small relay modules to be mounted on a printed circuit board strip. The printed circuit board is then terminated with an edge connector containing all the control lines for each relay. By supplying digital control signals to the edge connector, control of AC voltages of up to 220 V and DC voltages of up to 80 V is easily implemented.

Interaction between the computer and the operator is implemented using several different components. The graphics capabilities of the TRS-80 CRT will be used to display a schematic of the fluid conditioning system and display the status of all the components during the test. Also, an LED status display was developed using bi-colored LED's. Each LED represents a certain temperature or pressure and the status of that parameter; green for normal, red for marginal, blinking red for critical or failure. A printer provided hard copy containing the values of the test operating conditions, pressure, temperature, etc. LED's are also used to indicate the status of relay closure solenoids.

Diagnostic Hardware and Software Development for Field Application

The completion of the microprocessor test stand controller was the first stage of a program devised to develop the necessary hardware for a diagnostic system. The development program of the microprocessor test stand controller was two-fold: 1) The complete monitoring and control of the setpoints for a given test; i.e. inlet pressure, temperature, etc. 2) The complete data acquisition consisting of collection, reduction, and analysis. The test stand controller was designed with an

upward expandability towards the development of both the hardware and software for a dedicated field unit.

The test stand control unit was built with four major system modules in mind—system microprocessor, control and data acquisition, program storage, and human interface.

The use of a standard (STD) bus for the control interface of the test stand controller provides the upward capability towards a stand along diagnostic analysis unit. The test stand controller provided information concerning hardware capabilities of the microprocessor. With the fundamentals in hand, the next stage of data processing and analysis can be interacted into the capabilities of the test stand controller. The diagnostic system development would consist of using the microcomputer on the test stand controller. The test stand controller uses a commercially available microcomputer. Upon completion of the appropriate software, the transition to a dedicated field diagnostic unit would consist of replacing the microcmputer with a STD-bus-based Z80 microprocessor card. The developed software prototype on the microcomputer could be loaded into a nonvolatile type memory and installed in the STD bus.

Instrumentation

The instrumentation utilized in this project is illustrated in Figs. D-2 and D-3. The system represents the functions of signal transduction, conversion, analysis, and display. An accelerometer was the transduction device measuring the structural vibration of the test component. The

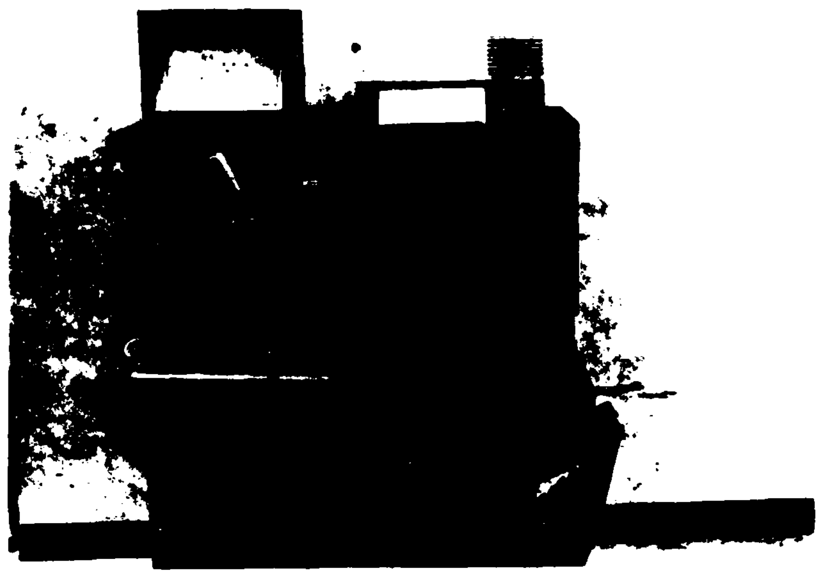


FIG. D-2. Microcomputer Test Control System

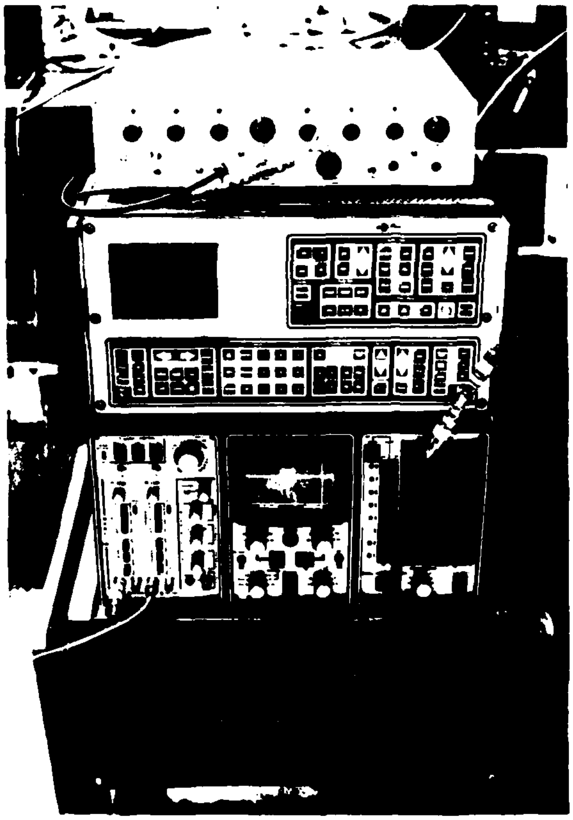


FIG. D-3. Test Analysis System

charge amplifier was utilized to amplify the electrical waveform from the transducer. The passband filter was utilized to filter out the frequencies within the signature outside of the desired analysis range The oscilloscope had the capability to digitize and store the real time signature on a floppy disc. The oscilloscope offers the capability of storing data in a digitized form which can be downloaded to a computer for further analysis. This gives the facility the capability of collecting data accurately which can be analyzed by a computer at a later time. This enhances the analysis capability of the data, for correlations of data can be manipulated through any software reduction programs which may be of interest.

The data reduction of the vibration signature is analyzed on a spectrum analyzer. The data are subsequently acquired, transformed, and stored in memory of the spectrum analyzer. The storage capability of the analyzer provided the comparison of a pump's baseline signature to a corresponding operating condition. The continuous improvements in the technology of spectrum analyzers will broaden the research capabilities in the area of vibration signature analysis.

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